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Anna Cretì *Editors*

Energy Transition, Climate Change, and COVID-19

Economic Impacts of the Pandemic

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Preface

The impact of COVID-19 pandemic is far beyond health implications. No other pandemic, including the Spanish Flu of 1918–1920, has had such a powerful impact on society. Every other aspect of the economy and society is being affected by it, including economic well-being, contraction in real economic activity, global energy systems, and the environment. There is a remarkable agreement that the energy sector, like many others, will evolve in the coming years under the impression of its consequences. Given the existence of ambitious policy goals aimed at reducing overall environmental and economic-related crises, the effects of COVID-19 on energy transition and climate change represent a challenging issue for both researchers and policymakers as unintended side effects of future conditions.

A range of spectacular policy responses to COVID-19, including travel restrictions, business closures, working, and learning from hope, have resulted in a significant reduction in economic activity and associated fossil fuel usage worldwide.

Consequently, many countries are claiming significant reductions in greenhouse gas emissions during 2020, driving them one step closer to the original emissions targets they committed under the Paris climate change agreement. While the pandemic may have accelerated progress toward these targets over the past year, will this trend continue throughout the next decade and beyond?

The unknown scope and duration of the pandemic and its associated economic shocks have resulted that energy security and clean energy transition becoming highly unpredictable. As a consequence, the answer to this question will depend, in part, on the long-term effect of the pandemic on economic activity, global energy consumption, and the policy instruments which will be implemented to mitigate climate change.

In this context, this book brings together a number of researchers to discuss the impact of COVID-19 on energy transition and climate change. It collects a wide range of high-quality theoretical and empirical studies at the nexus of the COVID-19 pandemic, energy, resource, and environmental economics. The contributions collect the most updated data in order to quantify the effects of the pandemics shocks.

Various COVID-19 impacts have been discussed: sustainability issues, potential for green recovery, air quality, likely long-term effects, the nexus between weather, pollution, and COVID-19 spread, fuel poverty and energy justice, energy demand and sustainability in developing countries, including Algeria, Morocco, and Saudi Arabia. The variety of the topics proposed allows to envisage an interesting range of policy responses to the different dimensions of the COVID crisis.

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Assessing the Relationship Between Air Quality, Wealth, and the First Wave of COVID-19 Diffusion and Mortality

Roberto Antonietti, Paolo Falbo, and Fulvio Fontini

1 Introduction

The COVID-19 disease, which spread out at the end of 2019, was declared, on the 11th of March 2020, as a pandemic by the World Health Organization. By April 21, 178 countries had confirmed cases of COVID-19 infection.[1] The total count of reported cases and casualties is still rising at the time of writing this chapter.

The pandemic is having a huge social and economic impact. Social distancing and lockdowns measures that have been adopted to limit its diffusion have severely limited industrial, commercial, and transportation activities. On the other hand, lockdown measures have had positive effects on the environment in general, such as better air and water quality, less pollution, and a lower anthropic pressure on several animal species (EEA, 2020). The relationship between the environment and the COVID-19 pandemic has also attracted attention because it was notable that the areas being hit the most by the virus were also among the most polluted of the planet. Wuhan and the province of Hubei, where the outbreak began, Lombardy in Italy, and the Madrid area in Spain, which have all heavily suffered from the viral infection, are regions with a very poor air quality.

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[1] Data obtained from the World Health Organization website: https://www.who.int.

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There is a twofold rationale behind the link identified between air pollution and the COVID-19 pandemic. First, it has been argued that poor air quality correlates with a greater diffusion of COVID-19 because atmospheric conditions favoring the permanence of airborne pollutants, such as particulate matter (PM), would also facilitate the spread of the virus conveyed by the droplets of human saliva floating in the air, which seems to be one of the main sources of contagion. PM could serve as a carrier of COVID-19 virus. Second, there may be a relationship between air quality and mortality due to COVID-19 infection because chronic exposure to environmental pollution in general and poor air quality in particular have a debilitating effect on the body, increasing its exposure to other respiratory diseases, and reducing the immune system's response to infections. All these effects can increase the mortality risk associated with COVID-19.

Research into these aspects is ongoing. By estimating an ecological regression model on the data of 35 US counties, Wu et al. (2020) provide evidence of the link between mortality rates and long period exposure to air pollutants (PM 2.5 in particular). Other published studies seem to confirm the above-mentioned links between air quality and coronavirus diffusion. Wu et al. (2020) estimated an 8% increase in the COVID-19 death rate associated with a rise of 1 mg/m^3 in PM 2.5 levels in some US regions. Ogen (2020) found a positive correlation between NO_x exposure and COVID-19-related mortality in 66 administrative regions in Italy, Spain, France, and Germany. Setti et al. (2020) found evidence of COVID-19 on outdoor PM in samples tested in the province of Bergamo (Lombardy, Italy), which experienced the highest diffusion and mortality rates in Italy (and among the highest worldwide). Fiasca et al. (2020) have estimated that an increase in PM 2.5 concentration by one unit corresponded to an increase of COVID-19 incidence rates of 1.56×10^4 people infection due to exposure. Other studies that have found a significant relationship between PM (2.5. or 10) and COVID-19 cases in Italy are Fattorini and Regoli (2020) and Bontempi (2020a). However, the evidence gained to date is not conclusive about the link between air quality and the diffusion of COVID-19 and the associated mortality (Bontempi, 2020b; Copat et al., 2020), in particular when taking into account countries' specificities.

Inspired by the evidence of the uneven diffusion of COVID-19 worldwide, and supported by recent results, such as in Sarmadi et al. (2020), who find an association between GDP, meteorological factors, and COVID-19 related variables, we check whether the macroeconomic structure of countries, as well as more direct factors like air pollution, plays a role in explaining the first wave of COVID-19 infection and death rates.

The rationales supporting our conjecture are the following. First, countries' different levels of wealth can be associated with more or less developed health care systems, in terms of facilities, personnel, and organization. Wealthier countries probably had a better chance of taking care of infected people and testing larger proportions of the population for contagion. This last aspect might also be a factor introducing a significant measurement bias in the way COVID-19-related hospitalizations and deaths have been counted.

At the same time, economic wealth interacts with air pollution levels. We know that a combination of less efficient production and transport systems, particularly in less developed countries, and a lower quality of energy consumption coincide with high environmental externalities (Sovacol, 2012). The cross-country data we use here confirm as much, showing a negative relationship between real per capita GDP and air pollution, as measured from the concentrations of small particulate (PM 2.5).

The role of agriculture needs to be considered as well, not just for its contribution to GDP, but also because of how it relates to air pollution. At a first glance, countries based largely on agriculture might be expected to be less exposed to air pollution, but high-tech and intensive animal breeding is associated with the extensive use of manure for fertilization, which is in turn associated with large particulate formation. Our analysis on the COVID-19 pandemic included both economic and environmental factors, so their interactions were tested too.

The contagion and death percentages observed around the world have been very different as well as those across the regions inside each country. Much of these differences is due to idiosyncratic factors, such as the early occurrence/isolation of a zero patient, the over-/under-evaluation of contagion risks on the side of local public health authorities, and so on (see, for example, Russo et al. (2020), and Villaverde and Jones (2020)). Therefore, to assess the relevance of macro socio-economic factors, whose influence is general and indirect, it is necessary to use cross section analysis, which smooths out idiosyncratic noise.

To develop our analysis, we merge data on worldwide country-level COVID-19 infections and deaths provided by the European Centre for Disease Prevention and Control (ECDC) and macro-economic data provided by the World Development Indicators of the World Bank group. Using a final sample of 142 countries, we first run a cross-sectional regression using, as the dependent variables, both COVID-19 infections and deaths, and, as main regressors, air pollution, wealth, and countries' total resident population. Then, we cluster countries according to their "economic similarity" and test the impact of air pollution on COVID-19 infections and mortality within each group.

This chapter is organized as follows: Section 2 presents the data and the preliminary analysis; Section 3 presents the cluster analysis and the results of the related estimates. Section 4 concludes.

2 Data and Preliminary Analysis

To build the dataset, we merge information from two sources. Data on COVID-19 infections (variable: INFECTIONS) and deaths (variable: DEATHS) are used to compute the dependent variables. They are drawn from the ECDC, an EU agency for the protection of European citizens against infectious diseases and pandemics. The data on the distribution of COVID-19 worldwide are updated on a daily basis by the ECDC's Epidemic Intelligence team, based on reports provided by national health authorities.[2]

Data for these two variables were collected for 5 days of the first wave of COVID-19 diffusion: March 24, March 31, April 7, April 14, and April 21, 2020. The COVID-19 outbreak did not develop everywhere at once, and national authorities have adopted different strategies and policies to deal with the pandemic. The first diffusion of COVID-19 has taken a certain amount of time. Countries have reacted to it with lockdown and other measures that have been implemented differently across time and countries. All these have affected the measurement of the effects of stock variables, and that is why we measure the effect of wealth and pollution on the diffusion and mortality of COVID-19 in different periods, from the start of the outbreak until the moment when the strictest lockdown measurers started to be lifted in the European countries have been hit earliest and most severely (Italy and Spain). At the beginning of our observation period, the relationship might have been influenced by the different pace at which COVID-19 was spreading around the globe. By the end of April 2020, lockdown measures were having an effect on the phenomenon. We nonetheless show stable, significant results across the dates selected, which means that our findings are robust to the timing of the virus diffusion and to the heterogeneity of the policies adopted. COVID-19 variables are merged with the data from the World Bank on:

- PM 2.5: mean annual exposure to PM 2.5 (micrograms per cubic meter).
- GDPPC: real per capita GDP (in 2010 US$ at PPP).
- POPULATION: total resident population.

Table 1 presents the summary statistics of these variables.

Table 2 shows the pairwise correlations of the total number of COVID-19 infections, and the total number of COVID-19-related deaths, with PM 2.5 exposure and real per capita GDP on 5 different days between March and April 2020.

Table 1 Summary statistics

Variable	Mean	Std. dev.	Min	Max
INFECTIONS 24/03	2648.04	10,336.8	1	81,553
INFECTIONS 21/04	17,028.93	72,148.47	6	787,752
DEATHS 24/03	114.98	625.48	0	6077
DEATHS 21/04	1196.82	4956.5	0	42,539
PM 2.5	28.43	20.32	5.861	99.73
GDPPC	15,661.6	20,679.9	370.74	10,9453
POPULATION (mln)	50.554	165.51	0.072	1386.4

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[2] For more information, see: https://www.ecdc.europa.eu/en/covid-19/data-collection.

Table 2 Correlations of COVID-19 infections and related deaths with PM 2.5 and GDPPC

	Infections				
	24/03	31/03	07/04	14/04	21/04
PM 2.5	−0.059	−0.132	−0.145*	−0.143*	−0.139*
GDPPC	0.200**	0.275***	0.276***	0.269***	0.261***
	Deaths				
	24/03	31/03	07/04	14/04	21/04
PM 2.5	−0.032	−0.100	−0.148*	−0.168**	−0.170**
GDPPC	0.107	0.177**	0.243***	0.274***	0.280***

***Significant at 1% level; **significant at 5% level; *significant at 10% level

Unlike the literature on air pollution and coronavirus diffusion, we find a negative correlation between the two, whereas the correlation between coronavirus (both infections and deaths) and wealth is positive.[3] For the number of deaths, we also note that all correlations become stronger and more significant toward the end of April.

We test the hypothesis that COVID-19 outcomes (both infections and deaths) have a significant relation with both PM 2.5 and real per capita GDP (while controlling for population) by means of a negative binomial regression. The analysis is replicated for each week from the 24 of March up to the 21 of April; for deaths, the first week is not considered to take into account the lag between the contagion and its consequences. Results are reported in Table 3.

We see that the estimated coefficient for PM 2.5 is not statistically significant when GDPPC is included as a regressor. This indicates that the relationship between pollution and COVID-19 might be spurious. However, we suspect that the socio-economic characteristics of each country might play a crucial role in explaining the link between pollution and COVID-19. To evaluate this, data are integrated with macro-economic information provided by the World Development Indicators of the World Bank on:

- IMPORT/GDP: import intensity (i.e., import value as a share of domestic GDP).
- AGRVA/GDP: agriculture value added as a share of GDP.
- MANVA/GDP: manufacturing value added as a share of GDP.[4]
- CO_2: CO_2 emissions (metric tons per capita).
- TEMP: average temperature in March (in °C).

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[3] We should stress that the correlation between PM 2.5 and COVID-19 infections or deaths is at country level, or *between* countries. It may be that, *within* countries, there is a higher level of contagion or mortality in regions where air quality is lower.

[4] We have omitted the share of services as a proportion of GDP (SERV/GDP) as an explanatory variable because it is collinear with AGRVA/GDP and MANVA/GDP.

Table 3 Infections and deaths: relationship with pollution and wealth

	Infections				Deaths		
NEG BIN	(1)	(2)	(3)	(4)	(2)	(3)	(4)
PM 2.5	−0.014	−0.013	−0.012	−0.012	−0.019	−0.020	−0.019
	(0.013)	(0.009)	(0.008)	(0.008)	(0.018)	(0.014)	(0.012)
GDPPC	0.00008***	0.0001***	0.0001***	0.00006***	0.00009***	0.00008***	0.00008***
	(0.00002)	(0.00002)	(0.00001)	(0.00001)	(0.00003)	(0.00002)	(0.00002)
POPULATION	0.016	0.013	0.012	0.012	0.020	0.018	0.017
	(0.016)	(0.011)	(0.010)	(0.008)	(0.020)	(0.017)	(0.014)
N	142	142	142	142	142	142	142
Pseudo R^2	0.050	0.043	0.040	0.038	0.053	0.053	0.053
Wald χ^2	23.37***	31.12***	34.63***	36.71***	30.39***	36.40***	41.92***
Alpha	2.753***	2.455***	2.394***	2.350***	3.862***	3.699***	3.585***
AIC	2013.67	2431.55	2553.44	2648.95	1437.10	1567.13	1662.30

(1) = March 24; (2) = April 7; (3) = April 14; (4) = April 21. Robust standard errors in brackets. Each estimate includes a constant term. ***Significant at 1% level; **significant at 5% level; *significant at 10% level

Table 4 Summary statistics

Variable	Mean	Std. dev.	Min	Max
IMPORT/GDP	0.458	0.250	0.116	1.825
AGRVA/GDP	0.099	0.098	0.0003	0.486
MANVA/GDP	0.128	0.063	0.010	0.374
CO_2 per capita	4.954	6.168	0.053	43.86
TEMPERATURE (March, °C)	14.83	11.47	−18.72	30.63

The import intensity measures the degree of (inward) trade openness of the economy; the agricultural and manufacturing value added considers the different GDP composition of the economy; The CO_2 emissions measure the relative efficiency in using energy as primary energy sources, accounting for both availability of hydrocarbon primary energy sources and technological development of the energy sector. Finally, temperature strongly relates with the geographical coordinates of countries and is suspected to play a crucial role in pandemic diffusions.

Since the World Bank provides information on PM 2.5 exposure up until 2017, we measure all the explanatory variables in the same year. The CO_2 variable has been included as a measure of the intensity and efficiency with which primary energy sources are used in a country to generate the aggregate output. Table 4 reports the summary statistics of these variables.

3 Cluster Analysis

The negative sign of the relationship between the impact of PM 2.5 on infections and deaths and the possible spurious correlation between COVID-19 and PM 2.5. deserves further examination. In this section, we check whether the association between air quality and COVID-19 outcomes changes across different areas of the world with respect to the economic structure and to climate-related variables. The 142 countries are grouped using Ward’s method, a well-known hierarchical approach to grouping observations (see Blashfield, 1980, for example). We identify seven clusters based on all the variables listed in Table 4. The composition of each cluster is represented in Fig. 1.

Table 6 reports the list of countries. Table 7 shows the eigenvectors of the correlation matrix, while the corresponding eigenvalues are shown in Table 8. Table 9 shows the mean values of each item in the clusters.

Cluster 1 is the group that explains the largest amount of the total variance. It includes many European countries and the USA: these countries share a high-income level, a large share of services as a proportion of their GDP, a high exposure to CO_2 emissions per capita, a small share of agriculture, and a low temperature in

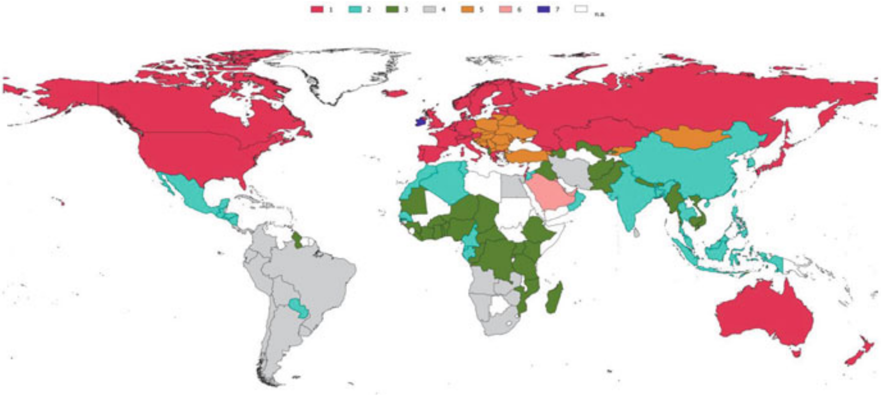

Fig. 1 Clusters of countries

March. Cluster 2 mainly comprises Eastern Asian and Northern African countries, which share a low weight of manufacturing as a proportion of domestic GDP and a moderately high import propensity. Cluster 3 is essentially made up of West Asian and Sub-Saharan countries, sharing a high openness to imports. Cluster 4 is a mix of countries sharing high CO_2 emissions and a high average temperature in March, e.g., countries below the Equator. Cluster 5 includes service economies sharing a low temperature in March. Cluster 6 contains high-income countries specializing in natural resource extraction. Cluster 7 pools four small open economies (three islands) with a large share of services and agriculture, and a moderately high level of CO_2 emissions.

We interpret the clusters using a linear discriminant analysis. We thus obtain linear combinations of the variables (the so-called canonical discriminant axes) that maximize the separation between the different classes/clusters. These axes are calculated to respect reciprocal orthogonality, so they can be used to plot individual data on a Cartesian space, to enable a visual inspection of the bivariate distribution of the clusters. Figure 2 shows the distribution of the 142 countries, grouped into the 7 clusters (using a different color for each cluster). Four clusters tend to stand out quite clearly. Clusters 7 and 1, on the right, denote high GDP levels. The countries they contain exhibit a high share of services as a proportion of GDP, and high levels of CO_2 emissions per capita, a low share of agriculture, and a low temperature in March. Cluster 7 is also characterized by high import levels. On the left, we see cluster 3, which is characterized by a high share of agriculture. In the middle, and lower down, we find cluster 4, with the lowest average import propensity. The remaining clusters 2, 5, and 6 are not neatly separable on Fig. 2, but Table 9 shows the average values of each cluster for the variables used in the cluster analysis.

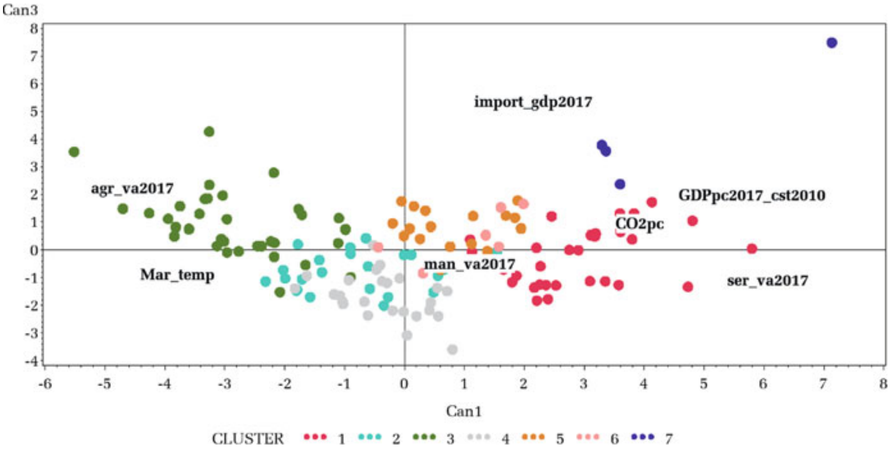

Fig. 2 Distribution of countries and clusters on the first two canonical axes

For each cluster, we adopt seven dummies, which take the value of 1 when a country belongs to the corresponding cluster. Then, we split our air pollution variable into seven new variables multiplying PM 2.5 levels by each cluster dummy (PM2.5$_i$*cluster *j*). As a final step, we estimate the following equation, one for COVID-19 infections and one for related deaths (both as on April 21, 2020), using a negative binomial regression model:

$$Y_{iT} = \gamma_0 + \sum_{j=1}^{7} \gamma_j \text{PM2.5}_i^* \text{ cluster (i)}_j + \beta_2 \text{POP}_i + u_{iT},$$

where *T* refers to the 21st, 14th, and 7th of April, respectively, and cluster (i)$_j$ =1 if country *i* belongs to cluster *j* and 0 otherwise.

Table 5 shows the results. In one case, namely cluster 1 (the wealthiest economies in the world), higher PM 2.5 concentrations (strongly) correlate with higher rates of infection and death (at each date). We also find evidence of a (weak) positive correlation between PM 2.5 and COVID-19 infections in cluster 5. In cluster 3, the association between PM 2.5 and COVID-19 outcomes is negative and strongly significant: these low-income countries are mainly in Africa and East Asia. Such a negative and significant estimated coefficient is nevertheless roughly ten times smaller than the positive coefficient of PM*cluster1. The same order of magnitude holds for the marginal effects at the mean: on April 21, a rise of 10 µg in PM 2.5 levels per cubic meter corresponds, on average, to 9850 more infections and 608 more deaths in cluster 1 countries and to 1430 less infections and 64 fewer deaths in cluster 3 countries.

Table 5 Correlation between pollution, wealth, and COVID-19 infections and deaths, by cluster

	Deaths			Infections		
NEG BIN	April 21	April 14	April 7	April 21	April 14	April 7
PM2.5*cluster1	0.304***	0.313***	0.333***	0.211***	0.223***	0.234***
	(0.053)	(0.056)	(0.058)	(0.045)	(0.046)	(0.048)
PM2.5*cluster2	−0.013	−0.011	−0.006	−0.020**	−0.020*	−0.016
	(0.013)	(0.018)	(0.019)	(0.010)	(0.010)	(0.012)
PM2.5*cluster3	−0.032***	−0.031***	−0.025***	−0.031***	−0.030***	−0.032***
	(0.009)	(0.009)	(0.010)	(0.007)	(0.007)	(0.008)
PM2.5*cluster4	0.038	0.043	0.053*	0.028	0.029	0.030
	(0.025)	(0.026)	(0.027)	(0.022)	(0.023)	(0.025)
PM2.5*cluster5	0.033*	0.031	0.031	0.039**	0.036**	0.031*
	(0.019)	(0.020)	(0.020)	(0.017)	(0.018)	(0.018)
PM2.5*cluster6	−0.010	−0.011	−0.010	0.013**	0.009	0.005
	(0.008)	(0.008)	(0.009)	(0.005)	(0.006)	(0.006)
PM2.5*cluster7	0.085	0.064	0.056	0.097*	0.082	0.067
	(0.117)	(0.107)	(0.102)	(0.055)	(0.064)	(0.061)
POPULATION	0.011**	0.010**	0.009*	0.010***	0.010**	0.010***
	(0.005)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
N	142	142	142	142	142	142
Pseudo R^2	0.068	0.072	0.078	0.047	0.049	0.051
Wald χ^2	128.1***	114.4***	95.96***	146.1***	127.8***	123.1***
Alpha	3.121***	3.138***	3.157***	2.081***	2.151***	2.151***

Robust standard errors in brackets. Each estimate includes a constant term. ***Significant at 1% level; **significant at 5% level; *significant at 10% level. Clusters are identified using the following variables: GDPPC, IMPORT/GDP, AGRVA/GDP, MANVA/GDP, SERVVA/GDP (services value added on GDP), CO_2 per capita and TEMP

At the same time, there is a limited negative relationship between air pollution and COVID-19 infections and related deaths for countries in cluster 3, which are mostly in Sub-Saharan regions (the poorest economies, largely based on agriculture) for which we cannot advance a plausible explanation. This puzzle might relate to data quality issues, especially with organizational difficulties and the costs of testing for the infection on large samples of the population.

4 Conclusions

In this chapter, we have analyzed the relationship between pollution, measured by concentration of PM 2.5, wealth, and COVID-19 worldwide during the first wave of the pandemic, taking into account the socio-economic characteristics of the countries. We have shown that air quality negatively affects both COVID-19 infections and deaths, but this is true only for the richest cluster of countries that are mostly located in the northern hemisphere. For the other countries, once they are grouped in different clusters according to their level and composition of GDP, trade openness, energy efficiency, and climate features, such a relationship does not hold anymore. This put evidence in favor of the possible linkage between COVID-19 diffusion and pollution through the socio-economic features of the most advanced countries.

There are several factors to consider regarding the quality of available data on COVID-19 that can influence our results. The first aspect concerns the homogeneity of the data collection process. Apart from costs and organizational problems, different policies have been adopted around the world concerning the use of testing for the infection and mitigation measures. There has been a generalized scarcity of test kits, which has influenced how the phenomenon has been measured. Overall, it is safe to assume that the official COVID counts fall abundantly short of the real number of infections around the world.

This may be true of the real number of deaths as well. There are non-trivial problems with certifying a death as being due to COVID-19. It preliminarily demands doing a test. Many of the elderly people infected with COVID-19 have been treated outside hospitals and died in nursing homes, adding to the difficulty of applying the test and establishing the cause of death.[5] Besides, a large proportion of the people dying with the infection are elderly and have underlying medical conditions, including cardiocirculatory and respiratory problems. In such cases, definitively establishing the ultimate cause of death is not always easy and can be costly and time-consuming.

Nevertheless, our analysis gives an account of the impact of air pollution and economic and environmental variables on the COVID-19 pandemic around the world. The study of this phenomenon is growing, and we welcome future analyses that include local and global factors to help explain the relationship between air pollution and COVID-19 pandemic, as done in this work.

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[5] In Italy, for instance, the classification protocol states that only people who die after officially testing positive in hospitals can be classified as COVID-19 victims. Some reports (e.g., Gabanelli & Ravizza, 2020) show that in several EU countries (e.g., the Netherlands, Belgium, among others), the mortality rate due to coronavirus remains particularly low, but in the first 4 months of 2020, these countries have had more than double the mortality rates of the same period in 2019. It is not clear why different countries count COVID-19-related deaths differently.

Appendix

Table 6 Clusters of countries

Cluster	Countries
1	Australia, Austria, Belgium, Canada, Cyprus, Denmark, Spain, Estonia, Finland, France, Germany, Georgia, Greece, Iceland, Israel, Italy, Japan, Kazakhstan, Lebanon, Latvia, Montenegro, The Netherlands, Norway, New Zealand, Portugal, Russian Federation, Sweden, Switzerland, The United Kingdom, The United States
2	Bangladesh, China, Cameroon, Algeria, Gabon, Equatorial Guinea, Guatemala, Honduras, Indonesia, India, Jordan, Korea, Rep., Morocco, Mexico, Malaysia, Nicaragua, Oman, Philippines, Paraguay, Senegal, El Salvador, Thailand, Tunisia
3	Afghanistan, Albania, Azerbaijan, Benin, Burkina Faso, Bhutan, Central African Republic, Cote d'Ivoire, Congo, Dem. Rep., Congo, Rep., Ethiopia, Ghana, Guinea, Gambia, Guyana, Iraq, Kenya, Cambodia, Liberia, Madagascar, Myanmar, Mozambique, Mauritania, Niger, Nigeria, Nepal, Pakistan, Rwanda, Chad, Togo, Timor-Leste, Tanzania, Uganda, Uzbekistan, Vietnam
4	Angola, Argentina, Belize, Bolivia, Brazil, Chile, Colombia, Cabo Verde, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, Egypt, Grenada, Iran, Jamaica, Sri Lanka, Namibia, Panama, Peru, Uruguay, South Africa, Zambia, Zimbabwe
5	Armenia, Bulgaria, Bosnia and Herzegovina, Belarus, Czech Republic, Croatia, Hungary, Kyrgyz Republic, Lithuania, Moldova, North Macedonia, Mongolia, Poland, Romania, Serbia, Slovak Republic, Slovenia, Turkey, Ukraine
6	United Arab Emirates, Bahrain, Brunei Darussalam, Kuwait, Qatar, Saudi Arabia
7	Ireland, Luxembourg, Malta, Singapore

Table 7 Eigenvectors of the correlation matrix

Cluster	Eigenvalue	Difference	Proportion	Cumulative
1	3.0519	1.9871	0.4360	0.4360
2	1.0648	0.1769	0.1521	0.5881
3	0.8879	0.1044	0.1268	0.7150
4	0.7835	0.1295	0.1119	0.8269
5	0.6540	0.2849	0.0934	0.9203
6	0.3692	0.1806	0.0527	0.9731
7	0.1886	–	0.0269	1

Table 8 Eigenvalues of the correlation matrix

Cluster →	1	2	3	4	5	6	7
GDPPC	0.480	0.147	−0.014	0.228	−0.045	0.747	−0.370
AGRVA/GDP	−0.484	0.199	0.125	0.091	−0.297	0.520	0.587
MANVA/GDP	0.124	−0.835	0.443	−0.120	0.078	0.213	0.161
SERVA/GDP	0.436	0.147	−0.291	−0.373	0.476	0.111	0.572
IMPORT/GDP	0.206	0.463	0.836	−0.076	0.108	−0.158	0.040
CO_2	0.390	−0.079	−0.033	0.757	−0.174	−0.280	0.399
TEMP	−0.368	−0.004	0.056	0.456	0.797	0.109	−0.078

Table 9 Average values of clusters

Cluster	Freq.	GDPPC	AGRVA/GDP	MANVA/GDP	SERVA/GDP	CO_2	IMPORT/GDP	TEMP
1	30	39,074	0.03	0.12	0.66	7.9	0.42	2.8
2	23	6217	0.09	0.20	0.53	3.5	0.39	21.1
3	35	1615	0.23	0.09	0.43	0.8	0.43	22.1
4	25	6758	0.07	0.10	0.58	2.6	0.33	22.1
5	19	10,809	0.06	0.16	0.54	5.0	0.61	2.0
6	6	35,377	0.01	0.12	0.52	26.3	0.49	21.8
7	4	66,405	0.01	0.16	0.70	10.1	1.39	10.6

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COVID-19 Recovery Packages and Industrial Emission Rebounds: Mind the Gap

Côme Billard and Anna Creti

1 Introduction

Since December 2019, the Covid-19 coronavirus has spread quickly from Asia to Europe and America, causing large-scale loss of life and severe human suffering (Financial Times, 2020). The pandemic represents the third and greatest economic, financial and social shock of the twenty-first century—after 9/11 and the global financial crisis of 2008 (OECD, 2020). From an environmental perspective, this unexpected episode could mark a turning point in the fight against global warming. This year, global greenhouse gas (GHG) emissions will fall by around 7%, representing the annual rate at which our economies should decarbonise to reach carbon neutrality in 2050.[1] Instead, emissions will rebound once mobility restrictions are lifted and economies recover (Le Quere, 2020), unless governments take actions.

The expected decline in 2020 GHG emissions comes as a consequence of national policies to prevent the spread of the virus (Helm, 2020).[2] Indeed, G20 nations have implemented restrictions (e.g. social distancing, mobility) slowing down economic systems (Thunström et al., 2020). On the supply side, around 81% of the global workforce has been hit by either full or partial lockdown measures, causing unprecedented job losses and furloughs (International Labour Office, 2020).

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[1] This objective ensures a temperature rise below 1.5°C degree by 2100 (UNEP, 2019).

[2] Suggesting we have not decoupled GDP growth and carbon emissions (Helm, 2020).

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On the demand side, consumer spending has fallen as it was no longer possible to travel, including to shop for discretionary items, go to restaurants or for experience-based activities (Center for Economic Policy Research, 2020). Overall, the crisis has impacted economic activity from both demand and supply sides (World Economic Forum , 2020), calling governments for unprecedented support policies.

Depending on objectives and timing, government support programs are either part of short-term rescue plans or long-term recovery plans. With respect to the former, numerous EU governments have already exposed and implemented fiscal rescue policies (International Monetary Fund, 2020). These emergency measures come as a short-run safety net to protect business balance sheets, reduce bankruptcies and address immediate human welfare concerns during lockdown periods.[3] Some rescue policies also cover emissions-intensive companies facing bankruptcy or significantly reduced revenue. For instance, this has been the case for airlines companies in France, Australia and the USA.[4] To ensure the success of the Paris Agreement (2015), government support plans (e.g. bailouts) should be conditional on these industries developing a measurable plan of action to transition towards a net-zero emissions future.[5] Indeed, the COVID-19 crisis will reduce global GHG emissions in 2020 but the long-term impact of the pandemic on emissions will be driven by forthcoming investment choices (both public and private). At the European scale, imminent recovery packages soon to be delivered will act as stimuli to restore economic growth in the region (Hepburn et al., 2020). The design of such packages (e.g. sectoral economic incentives, public investments) will reshape the economy on the long run, acting as a potential game-changer to reach a post-carbon Union by 2050 (McKinsey & Company, 2020).

A key objective of any recovery package is to stabilise expectations, restore confidence and to channel surplus desired saving into productive investment (Hepburn et al., 2020). While most European governments have implemented rescue packages (e.g. France, Germany, Italy, Spain and the United Kingdom), the European Commission announced an additional budget amount of €750 billion to support most affected EU economies, representing more than €1100 billion global budget for the period 2021–2027 (European Commission, 2020).[6] If this amount is necessary for EU economies to recover (e.g. France, Italy, Spain), an efficient long-run recovery plan should target sectors able to rapidly create jobs and boost

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[3] In April 2020, all G20 nations (including most EU member states), had signed such fiscal measures into law (see International Monetary Fund, 2020).

[4] Precisely, France rescue plan for Air France reached €7 billion (Les Echos, 2020); Australian government announced AU$715mn of unconditional Australian airline relief (through the Coronavirus Economic Response Package (Commonwealth of Australia, 2020), and US$32bn of bailouts for US airlines (see Courtney, 2020 for a review of CARES Act)).

[5] Which, for instance, has not been the case for Air France (Le Monde, 2020).

[6] Although governments will have flexibility regarding the allocation of such funds, the main priority is to reach the EU's objectives of climate neutrality and digital transformation, to offer social and employment support as well as to reinforce the EU's role as a global player (European Parliament, 2020).

production across other industries in the economy, thus stimulating GDP growth (Allan et al., 2020). Among other factors,[7] those targeted sectors should display high short-run/long-run economic multipliers, or return for every dollar of expenditure (Bussing-Burks, 2011; Ramey, 2019). Such metrics accounts not only for the effects of the spending (government expenses, tax reductions) in the specific sector (e.g. impact on income, output), but also for the subsequent rounds of spending generated by the initial expenditures in other parts of the economy.[8] Back during and following the 2008 global financial crisis, expansionary policies, focusing on investments through the lens of economic coefficients, were more effective at restarting economic activity than austerity-based policies (European Central Bank, 2015; Hepburn et al., 2020). Twelve years later, the COVID-19 crisis pushes again policy-makers to decide which key sectors to focus investments on, reflecting changing technologies and the need to stimulate growth and secure job creations for the coming years (DG Tresor, 2020).

From a climate policy approach, the sole consideration of economic multipliers to guide forthcoming economic stimuli does not guarantee a transition towards a post-carbon society by 2050 (Hammer and Hallegatte, 2020). Indeed, recovery plans could be either “brown” or “green” depending on their ability to decouple emissions from economic activity (IFRI, 2020). Sectors exhibiting high economic multipliers could be those acting as big emitters suggesting a tension between short-run economic growth and climate targets (see European Commission, 2007). Then, to decouple GDP growth and emissions, EU governments could be interested in understanding which industrial sectors are driving GHG emissions[9] in the economy. Following the ongoing crisis, the willingness to design green recovery plans could lead to not supporting such industries. By doing so, large amounts of GHG emissions could be avoided once economy recovers, putting the entire EU industrial system on track with respect to the Paris Agreement objectives. Moreover, some industries might not be greenhouse gas (GHG) intensive but might decrease global GHG emissions by limiting provision of inputs to downstream dirty sectors. When designing sectoral support policies, government will have to be aware of such intra-sector dynamics to limit emissions. This paper aims at providing new insights on these issues.

Precisely, we consider the economy as a system of industries interacting with each other (OECD, 2016) and capture the dynamics of supply/demand between industrial sectors. Indeed, output of an industry might be used directly as input or

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[7] Several other factors are relevant to the design of economic recovery packages: contributions to the productive asset base and national wealth, speed of implementation, affordability, simplicity, impact on inequality and various political considerations.

[8] In detail, economic multiplier measures the impact on activity of each additional currency unit of spending/tax cut funded by borrowing. A multiplier of 1 means \$1 extra spending boosts final production and income by \$1. A multiplier of 3 implies \$1 spending boosts final income and output by \$3.

[9] Gases that trap heat in the atmosphere (e.g. carbon dioxide, methane), contributing to global warming. See full description in the Sect. 2.

as output supplied to other sectors (e.g. output of the mining sector are consumed as inputs by that industry or supplied as inputs to other sectors). The decrease in production from the mining sector would decrease the sector output and impact the demand-side sectors. Then, following the chain of intermediate demand, industries directly connected such as basic metals would in turn reduce their output. Such a cascading mechanism of output contraction would decrease associated GHG emissions (i.e. from production).[10] While some studies have explored phenomenon of economic cascades (e.g. information in financial markets (Romano, 2007), the diffusion of risks in the banking system (Battiston et al., 2017) or the stranding of dirty assets in a low-carbon economy (Cahen-Fourot et al., 2020)), the topic of industrial emissions has never been investigated from a systemic perspective.

Overall, we propose a novel analysis of the process through which a contraction of the gross output of a specific sector would decrease the use of inputs in other sectors leading to a drop in associated emissions (i.e. forward oriented sectors). The supply of essential inputs to the rest of the economy is a matter of addressing primarily forward impact effects rather than backward effects (i.e. change in inputs affecting upstream sectors). In the context of post-COVID-19 recovery plans, this approach is particularly relevant as supply chains have been severely hit by government restrictions, and supply dynamics will be critical to avoid inflation in the post-COVID opening time-window (BNP Paribas—Economic Analysis, 2020). While governments will implement economic stimuli to secure high levels of supply, our paper identifies the sectors that should not benefit from recovery plans[11] and quantifies the impacts of such deliberate decision on emissions (i.e. avoided emissions). Providing such new results would allow policy-makers to account for these potential "avoided" emissions when designing green economic stimulus. We use data available for five European countries affected by the COVID-19 pandemic (i.e. France, Germany, Italy, Poland and Spain) to illustrate our model and achieve two main objectives.

First, we use Input–Output (IO) concepts to derive national economic matrices of *emission coefficients*, including the entire range of the industrial productive sectors. These coefficients capture the amount of emissions that would be reduced in a sector due to a unitary decrease in primary inputs[12] utilised by another (or the same) sector, considering both direct and indirect effects. For instance, these matrices are able to provide GHG emission reductions in the textile sector due to a drop in the plastics industry, both directly and through its intermediate effects on, for instance, chemicals. By doing so, we identify industries most likely to trigger large emission reduction cascades and those most exposed to such a dynamics (i.e.

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[10] In the following, we name "cascading process" such a dynamics of emission contraction.

[11] Such sectors drive GHG emissions in the industrial system. Without contributions in terms of climate strategy, the government willing to achieve climate goals should not target them.

[12] We define "primary inputs" as the main factors used in production (labour, capital, land and others). IO tables report their factor costs (e.g. compensation of employees, consumption of fixed capital or net operating surplus) (Miller & Blair, 2009).

increase in internal GHG emissions through the channel of another sector). The novelty of the present analysis is to maintain a systemic perspective of the national economy, and investigate the transmission channels of GHG emission reductions across industries (i.e. emission cascades). By providing a quantitative estimation of such cross-sectoral GHG emission interactions, our paper brings relevant insights to policy-makers too.

Whatever the economic system, we highlight how mining,[13] coke and refined petroleum products[14] and electricity and gas[15] are among the sectors with the largest emission coefficients. A fall in their activity (i.e. gross output) creates the largest reduction amount of emissions in the system. Leaving all else equal, green recovery packages should ensure their activity to not expand, and even further to contract.[16] On the opposite, coke and refined petroleum, basic metals[17] and electricity and gas industries are the most exposed to such dynamics of emission contraction. All these activities have various impacts in terms of GHG emission reductions (across economies), suggesting different national strategies regarding implementation of recovery plans.

Second, we focus our study on the mining industry in order to investigate the most relevant channels of sectoral cascades of GHG emissions that could be avoided in the future. By doing so, we are able to evaluate the role of energy intensive sectors such as coke and refined petroleum products, basic metals and electricity and gas in the cascading process. While countries exhibit different cascading dynamics depending on the peculiarities of their industrial structure, certain regular patterns emerge. On one hand basic metals, the manufacture of coke and refined petroleum products and electricity and gas are the activities the most directly exposed to a drop in GHG emissions through a contraction of production in the mining sector. Such results suggest strong economic connections between the mining industry and these sectors where the former supplies the latter.[18] On the other hand, irrespective to their rankings in the process, chemicals and pharmaceutical products[19] as well

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[13] The sector encompasses coal and lignite, crude petroleum and natural gas, metal ores, other mining and quarrying products and mining support services.

[14] Includes coke oven products and refined petroleum products.

[15] The sector mainly covers electricity, transmission and distribution services, manufactured gas, distribution services of gaseous fuels through mains, steam and air conditioning supply services, natural water, water treatment and supply services.

[16] If one assumes no shift towards cleaner production in those industries.

[17] The sector covers basic iron and steel and ferro-alloys, tubes, pipes, hollow profiles and related fittings, of steel, other products of the first processing of steel, basic precious and other non-ferrous metals.

[18] In some countries such as Germany and Poland, this finding is particularly relevant.

[19] Sector covers basic chemicals, fertilisers and nitrogen compounds, plastics and synthetic rubber in primary forms, pesticides and other agrochemical products, paints, varnishes and similar coatings, printing ink and mastics, soap and detergents and other chemical products.

as manufacture of other non-metallic mineral products[20] are highly present in the third layer of the GHG cascading process.[21] The latter emphasises the existence of a significant connection between those activities and aforementioned energy intensive sectors (e.g. chemicals affected by upstream coke and refined petroleum products activity). In addition, agriculture[22] and construction[23] are often impacted by mining decreasing activity through the channel of basic metals. From a policy perspective, these outcomes suggest that moving away from mining would have impacts not only on emissions (Fugiel et al., 2017), but would also generate economic effects on other sectors (i.e. from mining to downstream industries such as construction through the channel of basic metals). On this issue, our results complement the flourishing literature on assets at risk due to a low-carbon transition (Creti & de Perthuis, 2019). Such findings reinforce the importance of a well-designed recovery plan to limit GHG emission rebound effects and to stimulate sector-based clean solutions (e.g. green inputs).

The remainder of the article is organised as follows. Section 2 introduces the method to compute the matrices of sectoral *emission coefficients*. Section 3 presents the results of the analysis for five European countries, discussing the sectors most likely to create large amounts of emission reductions and the ones most exposed to such dynamics. Section 4 focuses on understanding the systemic propagation of shocks starting from mining in order to identify relevant channels of GHG emission decline. Finally, Sect. 5 discusses implications of our results for designing effective green recovery packages to avoid a resurgent increase in industrial GHG emissions and exposes elements of conclusion.

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[20] The activities include glass and glass products, refractory products, clay building materials, other porcelain and ceramic products, cement, lime and plaster, articles of concrete, cement and plaster, cut, shaped and finished stone.

[21] For non-metallic mineral products, the sector is present in the second or third layer, depending on the examined country.

[22] The sector includes non-perennial crops, perennial crop, planting material: live plants, bulbs, tubers and roots, cuttings and slips, mushroom spawn, live animals and animal products, agricultural and animal husbandry services (except veterinary services), hunting and trapping and related services, forest trees and nursery services, wood in the rough, wild growing non-wood product, support services to forestry, fish and other fishing products; aquaculture products, support services to fishing.

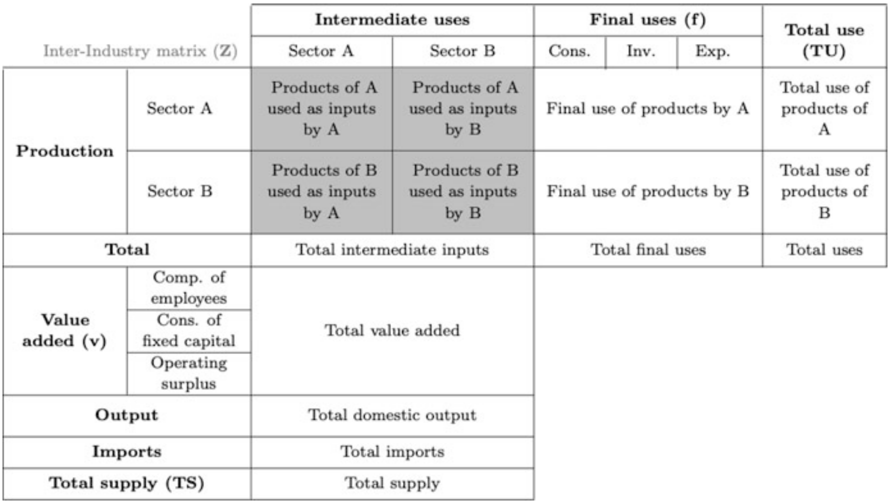
[23] Represents buildings and building construction works, roads and railways, construction works for roads and railways, constructions and construction works for utility projects; constructions and construction works for other civil engineering projects, demolition and site preparation works; electrical, plumbing and other construction installation works, building completion and finishing works, other specialised construction works.

2 Methodology and Data

2.1 *The Emission Reduction Multiplier Matrix*

Following Cahen-Fourot et al. (2020), we start with the national inter-industry matrix **Z**, a square matrix exhibiting amounts of sectoral intermediate consumption. In broad terms, such a matrix is called "Input–Output matrix" and captures exchanges of goods and services among industrial sectors in monetary units.[24]

In input–output tables (IOTs), the **Z** matrix usually comes with an additional set of column vectors displaying final consumption (i.e. demand (**f**)) and row vectors representing value added items (**v**) (i.e. compensation of employees, fixed capital consumption, gross operating surplus). Sectors appear both as producers of goods and services (rows) and as consumers of intermediate inputs (columns). More specifically, IOTs are commonly defined as monetary industry balances, where total supply $\mathbf{x}^T = \mathbf{i}^{\mathbf{T}}\mathbf{Z} + \mathbf{v}$ equals total use $\mathbf{x} = \mathbf{Z}i + \mathbf{f}$ of products and services per sector.[25] Therefrom, the total amounts of all transactions over a row (industry output allocated to each category of user (i.e. intermediate and final consumption)) equals the sum over the corresponding column (total industry input flowing from upstream sectors—other industries and value added items). The IOT also reports imported goods and services, which are again used either as intermediate inputs or as final demand. Figure 1 below shows a stylised version of an IOT.



<table>
<tr><td colspan="2" rowspan="2">Inter-Industry matrix (Z)</td><th colspan="2">Intermediate uses</th><th colspan="3">Final uses (f)</th><th rowspan="2">Total use (TU)</th></tr>
<tr><td>Sector A</td><td>Sector B</td><td>Cons.</td><td>Inv.</td><td>Exp.</td></tr>
<tr><td rowspan="2">Production</td><td>Sector A</td><td>Products of A used as inputs by A</td><td>Products of A used as inputs by B</td><td colspan="3">Final use of products by A</td><td>Total use of products of A</td></tr>
<tr><td>Sector B</td><td>Products of B used as inputs by A</td><td>Products of B used as inputs by B</td><td colspan="3">Final use of products by B</td><td>Total use of products of B</td></tr>
<tr><td colspan="2">Total</td><td colspan="2">Total intermediate inputs</td><td colspan="3">Total final uses</td><td>Total uses</td></tr>
<tr><td rowspan="3">Value added (v)</td><td>Comp. of employees</td><td colspan="2" rowspan="3">Total value added</td></tr>
<tr><td>Cons. of fixed capital</td></tr>
<tr><td>Operating surplus</td></tr>
<tr><td colspan="2">Output</td><td colspan="2">Total domestic output</td></tr>
<tr><td colspan="2">Imports</td><td colspan="2">Total imports</td></tr>
<tr><td colspan="2">Total supply (TS)</td><td colspan="2">Total supply</td></tr>
</table>

Fig. 1 A stylised input–output table (Cahen-Fourot et al., 2020)

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[24] See Miller and Blair, 2009; Cahen-Fourot et al., 2020.

[25] Note that **i** is a column vector of the same dimension of **Z**.

In economics, IOTs have been mainly used to evaluate direct and indirect effects of changes in final demand based on the Leontief inverse matrix (Leontief, 1951; Metzler, 1951; Chen, 1973; Velàzquez, 2006). Although the demand will be critical in defining the forthcoming dynamics of GHG emissions under recovery plans, the novelty of our analysis is to adopt a supply-side perspective. Namely, we capture those sectors providing lower amounts of inputs supplied to other sectors as a result of a one-unit decrease in their gross value added or, generally speaking, gross domestic product (i.e. forward oriented sectors); this allows us to capture associated decrease in emissions (described hereafter). The supply of essential inputs to the rest of the economy is a matter of addressing primarily forward impact effects rather than backward effects (i.e. change in inputs affecting upstream sectors). In the context of post-COVID-19 recovery plans, our methodology is relevant as the supply has been particularly hit by governments restrictions (e.g. mobility) and supply dynamics will be critical to meet forthcoming demand and avoid inflation (BNP Paribas—Economic Analysis, 2020). Governments, while implementing economic policies to support supply-side sectors, will have to be careful on the potential impact on GHG emissions.

A relevant approach for our study is the Ghosh (1958) supply-driven model.[26] The output of the Ghosh model is a matrix $\mathbf{B} = \mathbf{x}^{-1}\mathbf{Z}$ of *allocation* coefficients of the supply of a sector (i.e. output) to all other sectors. In the matrix $\mathbf{B}$, each element b_{ij} quantifies the share of sector i's output consumed by sector j. Then, the Ghosh matrix $\mathbf{G}$ is defined as:

$$\mathbf{G} = (\mathbf{I} - \mathbf{B})^{-1}$$

We then transpose $\mathbf{G}$ to be able to read the effects of changes in sectoral primary inputs over the columns (similarly to the Leontief system) of $\mathbf{G}^T$, where ^{T} denotes the matrix transposition. Each entry $g_{i,j}$ of $\mathbf{G}^T$ shows the change in output $\mathbf{x}$ in sector i that would result from a unitary change of primary inputs used in sector j. In general terms, a drop (or increase) of one monetary unit in primary inputs supporting production in sector i will generate a drop (increase) in the output of sector j by an amount equivalent to $g_{i,j}$.[27] In IO analysis, primary inputs cover items appearing on the rows below the inter-industry matrix (e.g. compensation of employees). As exposed in Cahen-Fourot et al. (2020), primary inputs represent the societal effort to produce the output of a sector, captured by factor payments.

We innovate by combining the obtained Ghosh matrix with sectoral data of GHG emissions e.[28] To do so, we define $E_i = e_i/M_i^d$ as the emission intensity of sector i, where M^d represents the domestic output of the sector. By multiplying the diagonalised form of the vector of emission intensities by the Ghosh matrix, we find the matrix $\mathbf{S}$ of *emission reduction coefficients*:

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[26] Augustinovics, 1970; Beyers, 1976.

[27] Note that $g_{i,j}$ includes both direct and indirect effects.

[28] Cf. next part for full description of data.

$$\mathbf{S} = \hat{E}\mathbf{G}^T$$

Each element s_{ij} of matrix **S** represents the change in emissions in sector *i* generated by a unitary change of primary inputs used by sector *j*. For our purpose, the elements of **S** capture the amount of emissions of a sector *i* that could be reduced because of a unitary decrease in primary inputs used in the production of goods and services of another sector *j* (e.g. hard coal, iron ores). The column sum of matrix **S** gives a measure of the total amount of reduced emission resulting from a unitary reduction of primary inputs in a sector *j*. We define this as the total *emission coefficient* of a sector:

$$s_j^{TOT} = \mathbf{i}^T\mathbf{S}$$

where n is the dimension of matrix **S**. In our case, we assume the values of s_i^{TOT} to be largely driven by i emission intensity and therefore, by potential amounts of internal emission reduction. On the opposite, to estimate external *emission reduction coefficient* (i.e. the impacts of a sector reduction of primary inputs on emissions of all other sectors), we proceed as follows:

$$s_j^{EXT} = s_j^{TOT} - s_j^{diag}$$

where s^{diag} refers to the *j*-th element of the diagonal of **S**. In the end, we define the sum of the rows of **S** as the exposure of a sector to emission reductions (i.e. the reduction of emissions following a unitary loss in primary inputs used in all other sectors):

$$s_i^{EXP} = \mathbf{Si}$$

Overall, this methodological approach allows us to investigate both internal and external emission reductions generated by sectors. A sector might have large emission reduction coefficients mainly driven by internal reductions—suggesting a poor economic connection with other sectors (supply). We capture this feature in Sect. 3 by constructing the channels of reduction cascades across economies.

2.2 Datasets: Input–Output Tables and Emissions

We apply the methodology described above to five European economies, heterogeneously affected by the pandemic crisis: France, Germany, Italy, Poland as well as Spain (OECD, Economic Outlook, 2020; The Guardian, 2020). The main source of

Table 1 Breakdown of examined NACE sectors

Sector	Code	Sector description
A	1	Agriculture, forestry and fishing
B	2	Mining and quarrying activities
C10–12	5	Food products, beverages and tobacco
C13–15	6	Textiles, wearing apparel, leather and related products
C16	7	Wood and of products of wood and cork (except furniture)
C17–18	8	Paper products and printing
C19	9	Coke and refined petroleum products
C20–21	10	Chemicals and pharmaceutical products
C22	11	Rubber and plastics products
C23	12	Other non-metallic mineral products
C24	13	Manufacture of basic metals
C25	14	Fabricated metal products, except machinery and equipment
C26	15	Computer, electronic and optical products
C27	16	Electrical equipment
C28	17	Machinery and equipment n.e.c.
C29	18	Motor vehicles, trailers and semi-trailers
C30	19	Other transport equipment
C31–33	20	Other manufacturing, repair and installation of machinery and equipment
D–E	21	Electricity, gas, water supply, sewerage, waste and remediation services
F	22	Construction

IO tables data we employ is extracted from the OECD for the year 2015.[29] More precisely, we use symmetric input–output tables at basic price by industry.[30] Table 4 in the Appendix lists NACE level 1 categories,[31] while Table 1 below offers the detailed disaggregation of industries we investigate in this paper.[32] In the following, we deliberately exclude business services (Table 4, from G to S) as it represents a small share of emissions (OECD, Air Emission Accounts).[33] However, by providing inputs to other sectors, such activities can still play a significant role by driving down emissions. Our model allows us to capture such dynamics through the channel of external coefficients. With respect to emissions, we constructed our dataset from the OECD—Air emission accounts on total GHG emissions per sector (CO_2 eq.)

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[29] OECD Statistics: https://stats.oecd.org/Index.aspx?DataSetCode=IOTSI4_2018.

[30] Total economy, product by product in million $.

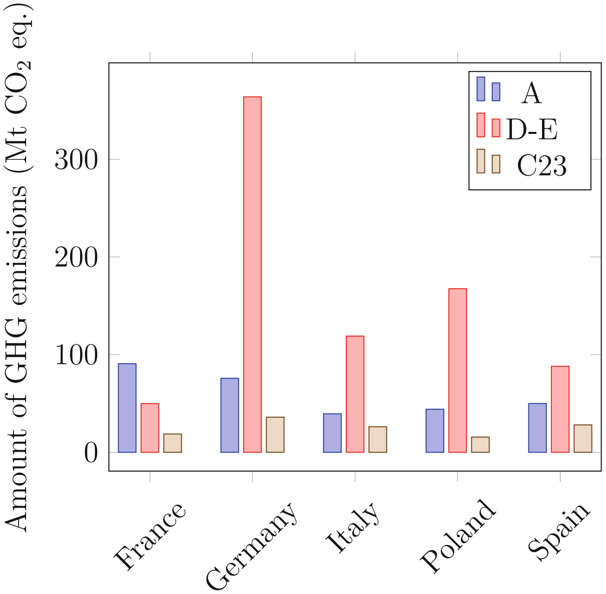
[31] The statistical classification of economic activities in the European Community, abbreviated as NACE, is the classification of economic activities in the European Union (EU).

[32] For further descriptions, refer to the Appendix.

[33] Exposed by Cahen-Fourot et al. (2020): The decarbonisation process might not be particularly detrimental for services activities (low dirty capital levels, low demand for fossil fuel).

for the year 2015.[34] Overall, Germany emitted more than 629 Mt (CO_2 eq.), followed by Poland (297 Mt), Italy (258 Mt), France (247 Mt) and Spain (221 Mt).[35] Although countries exhibit different patterns in terms of sectoral emissions, our dataset suggests that agriculture, electricity and gas, chemicals, fabricated metal products and basic metals were the largest emission intensive activities in 2015.

By combining IOTs and data of emissions, we are able to offer results for the industrial and power sectors (i.e. NACE from A to F) in France, Germany, Italy, Poland and Spain. In 2015, these countries represented more than 60% of the European Union gross domestic product (Statista, 2020).



Distribution of total GHG emissions (CO_2 eq.) across Agriculture (A), Electricity and Gas (D–E) and Other Non-metallic mineral products (C23)

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[34] OECD Statistics—"Data refer to total emissions of CO2 (CO2 emissions from energy use and industrial processes, e.g. cement production), CH4 (methane emissions from solid waste, livestock, mining of hard coal and lignite, rice paddies, agriculture and leaks from natural gas pipelines), N2O (nitrous oxide), HFCs (hydrofluorocarbons), PFCs (perfluorocarbons), (SF6 + NF3) (sulphur hexafluoride and nitrogen trifluoride), SOx (sulphur oxides), NOx (nitrogen oxides), CO (carbon monoxide), NMVOC (non-methane volatile organic compounds), PM2.5 (particulates less than 2.5 µm), PM10 (particulates less than 10 µm) and NH3 (ammonia)".

[35] These data cover the scope of our analysis (e.g. services are not included, imported emissions neither).

3 Cascading Greenhouse Gas Emissions

3.1 Emission Coefficients

In this section, we analyse results reported in Table 2 below, namely total emission coefficients (1), external coefficients (2) and exposure to emissions (3). We focus on the top five sectors for each country. Given the distribution of emissions in the economy and leaving all else equal, the first two sets of coefficients show the sectors that are likely to generate the largest amounts of GHG emission reductions (Mt CO_2 eq.) in the economic system following a unit decrease in their primary inputs. For the purpose of our paper, these sectors are the ones that should not be supported by forthcoming recovery plans if governments are willing to decouple growth and emissions. On the opposite, recovery plans could create economic incentives to engage such sectors in cleaner production processes (cf. Sect. 5). The third set of results displays instead the sectors that are likely to be most exposed to such dynamics of decreasing emissions from a unitary drop[36] distributed equally across all industries.

Table 2 Emission coefficients

France	Germany	Italy	Poland	Spain
Total emission coefficients (1)				
B (0.0292)	B (0.0190)	B (0.0373)	B (0.0121)	B (0.0286)
C19 (0.0058)	D–E (0.0055)	C19 (0.0081)	D–E (0.0118)	C19 (0.0061)
C24 (0.0035)	A (0.0051)	D–E (0.0044)	C19 (0.0073)	C23 (0.0057)
A (0.0030)	C19 (0.0044)	C23 (0.0032)	C24 (0.0062)	D–E (0.0040)
C23 (0.0028)	C24 (0.0027)	C24 (0.0028)	A (0.0054)	C24 (0.0027)
External emission coefficients (2)				
B (0.0287)	B (0.0178)	B (0.0359)	B (0.0088)	B (0.0280)
D–E (0.0004)	C19 (0.0008)	M (0.0007)	C20–21 (0.0019)	C20–21 (0.0008)
C19 (0.0004)	G (0.0005)	K (0.0007)	C19 (0.0016)	D–E (0.0008)
C22 (0.0004)	M (0.0004)	C24 (0.0006)	C24 (0.0015)	C22 (0.0007)
C25 (0.0004)	C25 (0.0004)	C19 (0.0006)	C28 (0.0013)	K (0.0006)
Exposure to emission coefficients (3)				
C19 (0.0225)	D–E (0.0114)	C19 (0.0268)	D–E (0.0142)	C19 (0.0205)
D–E (0.0042)	C19 (0.0083)	D–E (0.0141)	C19 (0.0058)	D–E (0.0104)
C24 (0.0029)	C24 (0.0036)	C24 (0.0026)	A (0.0053)	C24 (0.0039)
A (0.0026)	A (0.0017)	C23 (0.0016)	C24 (0.0029)	C23 (0.0031)
C23 (0.0012)	C23 (0.0017)	C20-21 (0.0009)	C23 (0.0021)	A (0.0015)

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[36] In primary inputs.

Regarding total coefficients, sector of mining (B) is by far the most prevalent, appearing as the top sector in every country of our scope.[37] Studying the S matrix, one can notice that emissions of sectors often significantly affected by the drop in primary inputs originating in the mining industry include those from coke and refined petroleum products (C19), electricity and gas industry (D–E), other non-metallic mineral products (C23) and basic metals (C24). These results emphasise the critical presence of mining inputs in their production process (e.g. iron ores, coal). For certain countries (e.g. Germany, Italy, Poland), the presence of D–E sector is likely to be mainly driven by the proportion of energy producing inputs in the energy mix (e.g. coal/gas, see EU data, Energy statistical datasheets for the year 2015).

In addition to B activities, industries included in category C (manufacturing) such as C19 (coke and refined petroleum products), C23 (other non-metallic mineral products), C24 (basic metals) and D–E (electricity and gas) exhibit large coefficients of emission reductions across economic systems.[38] The latter appears to be strongly intertwined with the level of emission intensity of the sectors, thus highlighting a significant potential for an internal emission decline. Moreover, for the specific case of other non-metallic mineral products (C23), examined EU countries were the largest producers in the EU in 2015 (European Commission, 2017). The strong potential for internal emission contraction in these industries is confirmed by the following analysis on external emission coefficients. Finally, agriculture (A) is among the top sectors of total emission coefficients in France, Germany and Poland. This outcome emphasises the key role of agricultural practices in climate mitigation strategies (IPCC, 2014).

External emission coefficients, which abstract from internal emissions of a sector and thus offer an accurate representation of the effect of a sector's activity on GHG emission decline in the rest of the economy, exhibit a different pattern. The relevance of mining (B) as an import-intensive activity is still highly significant (i.e. coefficients), confirming a strong economic connection (i.e. provider of inputs) between this sector and other high polluting sectors (e.g. coke and refined petroleum products (C19) and electricity and gas (D–E)).[39] With respect to other GHG intensive sectors, coefficients are drastically reduced. Sectors C20–21 (chemicals

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[37] Remember that total coefficients are column sums of the S matrix, thus representing the cumulative impact of a drop in a sector's primary inputs on GHG emissions of other sectors. As to interpret the coefficient of mining: a one-unit decrease (in monetary unit = million $) in mining primary inputs leads to a drop in GHG of 0.029 Mt (CO_2 eq.) across all other sectors in the economy. Looking at the S matrix and the impact of mining on coke and refined petroleum products (C19) we have: a one-unit decrease (in monetary unit = million $) in mining primary inputs leads to a drop in GHG from the coke and refined petroleum industry of 0.020 Mt (CO_2 eq.).

[38] Note that for France, D–E is not among top sectors. We expect the latter to be due to the large share of nuclear power generation in the country.

[39] Note that mining external coefficients are significantly high, embodying the ability of the sector to generate emissions in other GHG intensive sectors. Moreover, mining products are mainly imported from outside of the EU, thus explaining low amounts of emissions for the sector (although

and pharmaceutical products) become particularly relevant in Poland and Spain while C19 (coke and refined petroleum products) and C24 (basic metals) are the most recurrent manufacturing sectors in our sample (except in Spain). All these sectors appear high in the ranking of external emission coefficients because they provide significant amount of inputs to other productive sectors (thus driving up emissions).[40] For instance, both sectors B (mining) and C20–21 (chemicals) provide substantial intermediate goods to coke and refined petroleum products (C19) while basic metals (C24) supply fabricated metal products (C25) as well as machinery and equipment (C28). Table 3 below offers a closer look at industries exhibiting largest coefficients, reporting the top 5 sectoral values for the external emission coefficients originating in mining (B).[41]

As mentioned, C19 (coke and refined petroleum products), C24 (basic metals) and D–E (electricity and gas) all appear as the sectors most exposed to a decrease in GHG emissions through the channel of mining. Again, this matches previous observations that top industries in external emission coefficients provide substantial inputs to GHG intensive sectors.[42] Moving back to Table 2, several other manufacturing sectors appear among the top 5. For instance, this is the case for activities C22 (rubber and plastics) and C25 (fabricated metal products) in France, Germany and Spain, respectively. Note that financial and insurance activities (K) are also present in Italy and Spain.

Finally, looking at the values of total sectoral exposure to emissions, we can identify four main sectors, repeatedly appearing among the sectors with the highest row sums in S: C19 (coke and refined petroleum products); C23 (other non-metallic mineral products); C24 (basic metals) and D–E (electricity and gas). These sectors, in addition to having high emission intensities, are affected by multiple relevant inward economic links. To investigate these features, we consider the S matrix as an

Table 3 Sectoral emission coefficients for top sectors (excluded)

France	Germany	Italy	Poland	Spain
B (0.0292)	**B (0.0190)**	**B (0.0373)**	**B (0.0121)**	**B (0.0286)**
C19 (0.02094)	C19 (0.0072)	C19 (0.0236)	D–E (0.0038)	C19 (0.0171)
D–E (0.0032)	D–E (0.0070)	D–E (0.0095)	C19 (0.0027)	D–E (0.0061)
C24 (0.0018)	C24 (0.0022)	C24 (0.0012)	C24 (0.0010)	C24 (0.0023)
A (0.0009)	C23 (0.0004)	C23 (0.0005)	A (0.0004)	C23 (0.0012)
C23 (0.0007)	A (0.0003)	C20–21 (0.0002)	C23 (0.0004)	C20–21 (0.0005)

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in Poland, the sector displays a high amount of emissions as the country is the biggest EU hard-coal producer Reuters, 2020).

[40] The low level of external emissions coefficients of energy intensive sectors is due to the fact that downstream sectors are not huge polluting industries (e.g. machinery and equipment (C27), construction (F)).

[41] We exclude respective country top sector itself, to abstract from internal emissions.

[42] Although for electricity and gas, this argument depends on considered energy used (gas, coal).

adjacency matrix for a directed network (Godsil & Royle, 2013; Halleck-Vega et al., 2018; Cahen-Fourot et al., 2020), interpreting productive sectors as the vertices of the network and the $s_{i,j}$ elements of S as the weight of the edges going from vertex j to vertex i. Then, it is possible to represent the network as a circular layout. Figures 2 and 3 below show the outcome of this procedure for Germany and Spain, as they exhibit different patterns in terms of sectors' exposure (e.g. strength of coefficients and rankings).

When studying networks' characteristics, if one considers the potential strength (weight) of forward emission links,[43] mining activities (B) as well as coke and refined petroleum products (C19) and fabricated metal products (C25) are the leading sectors in Germany while mining (B) together with chemicals (C20–21) and electricity and gas (D–E) display the largest impacts in Spain. Interestingly, in Germany the most important GHG emission links start from B to coke and refined petroleum products (C19) and electricity and gas (D–E). The latter could be partly explained by the coal and gas dominating roles in the German power generation system (International Energy Agency, Key energy statistics, 2018). For Spain, top emission connections follow the same pattern: They start from mining

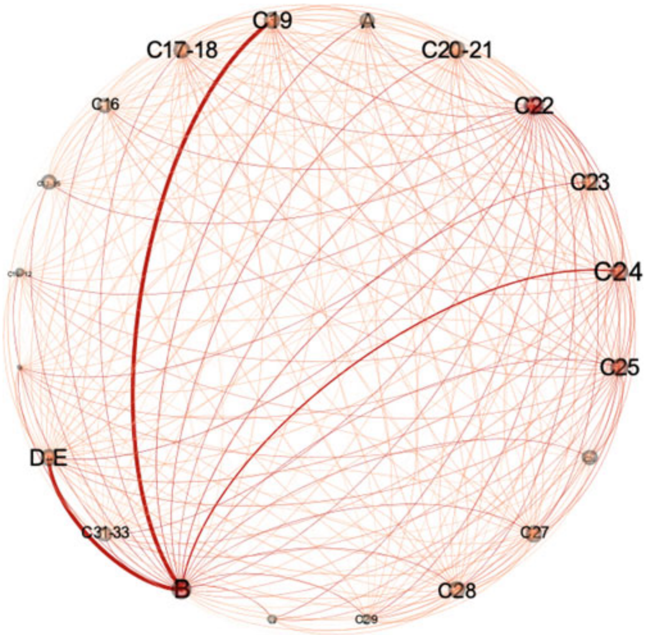

Fig. 2 Network of emissions across sectors in Germany. The size of the node is proportional to the number of weighted incoming links

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[43] Thus suggesting a strong effect of reducing gross domestic output in these sectors on other sectors' GHG emissions.

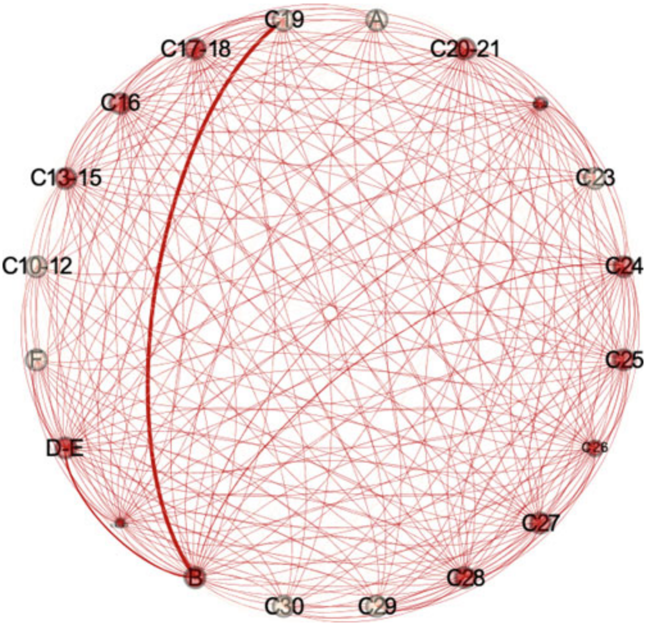

Fig. 3 Network of emissions across sectors in Spain. The size of the node is proportional to the number of weighted incoming links

(B) towards coke and refined petroleum products (C19), electricity and gas (D–E) and basic metals (C24). Comparing both countries, one can note on Figs. 2 and 3 the significant weight of emission links from mining (B) to electricity and gas (D–E), coke and refined petroleum products (C19) and basic metals (C24) in Germany. The latter provides a clear view of the strong role of mining (B) in the industrial German ecosystem.

Overall, our results emphasise different aspects: First, mining (B) is the sector most able to drive down external emissions, exhibiting strong links/connections to high polluting activities.[44] The sector deeply affects coke and refined petroleum products (C19) as well as basic metals (C24) and electricity and gas (D–E) industries. For this reason, we observe these industries to be ranked top in exposure category. Moreover, the ranking of coke and refined petroleum products (C19), chemicals (C20–21) as well as basic metals (C24) among the top external emission activities suggests a strong connection of these sectors to others across the economy—thus acting as facilitators in the shock propagation process originating from mining (B). The strength of such edges informs policy-makers not only on the dependence of sectors to others, but also on the ability of key industries to reduce emissions elsewhere in the economy.

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[44] Although mining is not emitting large amounts of emissions, cf. Table 5 in the Appendix.

In the next section, we investigate this feature. We map the cascade of GHG emission contractions from top external coefficients activities. By doing so, we are able to capture the key sectors acting as drivers of emission reductions in the industrial system. The latter brings us a clearer perspective on the existence of common or various patterns of cascades of emission contractions across countries.

4 Channels of Emission Cascades

After having shown the emission potential and associated exposure for the entire range of productive sectors, we shift our attention to top external multiplier activities (B activities). Our objective is to better investigate the propagation channels of decreasing GHG emissions due to a contraction (gross output) originating from the fossil fuel industry (e.g. coal and gas). Precisely, we trace out the propagation process throughout the industrial system to capture relevant patterns across economies.

We start by identifying the most relevant emission links resulting from a unitary drop of primary inputs supporting the production of mining (i.e. the largest values appearing on the B column of matrix S). We retain only the top q percentile of the values and position the affected sectors on the first layer of our cascade network. We repeat the procedure for the sectors in the first layer, identifying the sectors within the top q percentile of emissions originating in the layer. The weight of the resulting network edges is re-weighted to take into account that the fall in primary inputs in these sectors will be lower than one and a function of the strength of the upper edges. In other words, the emission reduction links tend to be stronger the closer they are to the shock origin, and get gradually weaker as they cascade downwards. We then repeat the same procedure for each layer, excluding the sectors that had already appeared in upper layers, until no new sectors appear. The results of this procedure are shown for each country belonging to our sample following a hierarchical layout (cf. Figs. 4, 5, and 6 below, for $q = 0.2$). The numerical weight of the top 10 edges is shown for reference.[45]

As expected, the sectors in the first layer of the network overlap with the ones reported in Table 2. The strongest emission link is the one flowing from mining (B) to coke and refined petroleum products (C19) for France, Germany, Italy and Spain. Interestingly, the reduction link from mining (B) to electricity and gas (D–E) has a larger weight in Poland while reaching an identical level compared to coke and refined petroleum products (C19) in Germany. The latter confirms previous observations on the carbon intensity of power systems in those economies. Manufacturing activities, especially basic metals products (C24), other non-metallic mineral products (C23) as well as electricity and gas (D–E), also frequently appear among the sectors most strongly affected by the immediate

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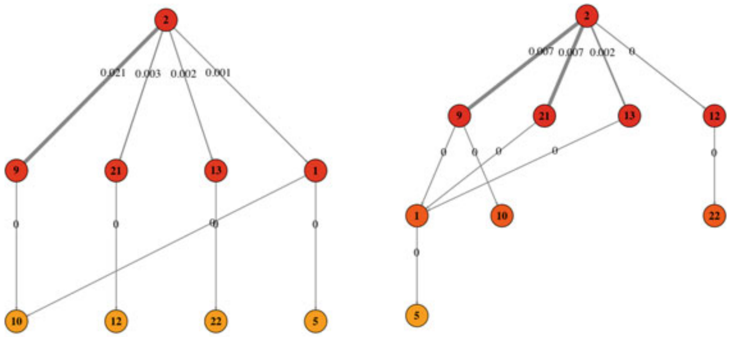
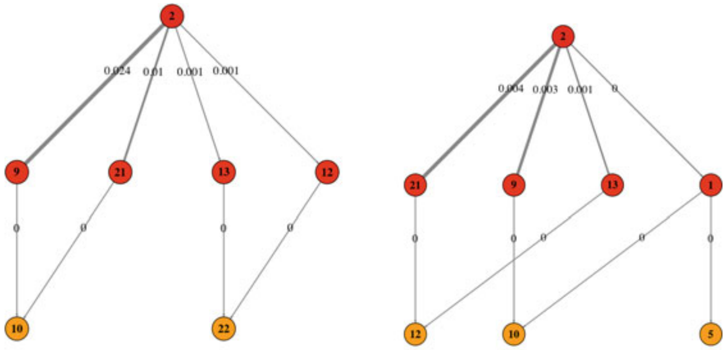
[45] Although most of them exhibit a weight of 0, the impact on downstream sectors remains higher compared to other industries.



a,b, France (left) and Germany (right)

Fig. 4 Hierarchical networks of emission cascades across economic sectors in France (left) and Germany (right)



c,d, Italy (left) and Poland (right)

Fig. 5 Hierarchical networks of emission cascades across economic sectors in Italy (left) and Poland (right)

contraction caused by mining (B). From the electricity and gas sector (D–E), the emission cascade often continues, further affecting chemicals (C20–21) or other non-metallic mineral products (C23) (cf. Germany, Italy, Poland, Spain). Given the strength of the original emission connection from mining (B) to electricity and gas (D–E), these links are often the most relevant after the ones affecting sectors in the first layer, and are justified by both the high emission intensity of the sectors and their large consumption of energy products (e.g. electricity, gas). From coke and refined petroleum products sector (C19), the most common cascades proceed through the chemical sector (C20–21)[46] while from basic metals sector (C24), GHG emission cascade propagates through the construction sector (F) and agriculture (A).

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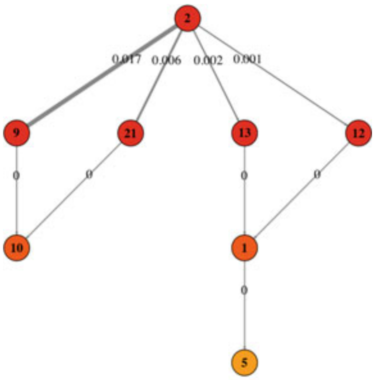
[46] Note that it is relevant in every country of our sample.

Fig. 6 Hierarchical network of emission cascades across economic sectors in Spain



e, Spain

Although surprising for agriculture (A), this finding looks intuitive for construction (F) as the sector relies on a high amount of metallic materials used as inputs (e.g. tubes, pipes).

In addition to the sectors mentioned above, several other sectors frequently appear in the cascade networks. For instance, food products activities (C10–12) often appear on the third or fourth layer of the network, regularly affected by links originating from agriculture (A) (cf. France, Germany, Poland and Spain). The sector in the C23 category (other non-metallic mineral products) also often appear, largely affected by B (mining) and further impacting F industries (construction). Overall, energy intensive sectors are highly present in the second layout of the networks, acting as propagation facilitators towards sectors supplying final demand side of the economy. These sectors exhibit low levels of emissions, thus not appearing in the network we observe here (e.g. textiles (C13–15), computer and electronics (C26)).

Studying the structure of the networks in conjunction with the weight of edges, we can identify two common cascades across countries. First, in all economies except Poland, a strong reduction cascade passes through coke and refined petroleum products (C19) and then affects chemicals (C20–21). This dynamics is particularly relevant in France, Italy and Spain. Although not appearing, we expect further downstream sectors to be manufacturing sectors (rubber and plastics products (C22), paper products and printing (C17–18)). Second, the cascade starting from mining (B) to electricity and gas (D–E) and then impacting manufacturing sectors such as chemicals (C20–21) and other non-metallic mineral products (C23) is widely present in our sample—and particularly significant in Poland, Germany and Italy.

Overall, the main structure of emission cascades spreads from mining (e.g. coal, gas, iron ores) to energy intensive manufacturing sectors (coke and petroleum products, steel, iron, chemicals) and power generation (e.g. electricity and gas), then further affecting industrial sub-sectors supplying final demand (e.g. construction, agriculture). In addition, GHG emission cascades share common characteristics across countries, suggesting the opportunity for EU governments to design green recovery packages sharing common patterns, aiming at limiting emission rebounds in sectors identified (e.g. mining (B), coke and refined petroleum products (C19), chemicals (C20–21) and electricity and gas (D–E)). The next section concludes by discussing the implications of such results for the design of green recovery packages. Indeed, further contractions of the identified sectors would lead to additional reduction of GHG emissions. However, it is more than likely that governments will create incentives to green the activity of such sectors (e.g. allocation of funds conditional on developing a climate strategy). We expose some policy avenues that could be implemented to limit emissions to rebound in those sectors.

5 Discussions and Conclusion

In the coming months, COVID-19 economic recovery packages will be introduced by governments in the EU. These packages will shape EU's future prosperity and determine the success environmental targets recently set in the Green Deal (European Commission, 2019). So far, we have identified industrial sectors that, if government wish to decouple growth and emissions in the coming decades, should not be benefit from forthcoming economic stimuli. If mining activities (B) play a significant role (by providing inputs to other sectors), emission intensive industries will have a particular contribution to meet the Paris Agreement targets. For those sectors, forthcoming economic stimuli (e.g. public investments) should be conditional on these industries developing a measurable plan to limit GHG emissions in the future.

Moving back to channels of emissions, coke and refined petroleum products (C19), chemicals (C20–21), other non-metallic mineral products (C23), basic metals (C24) and electricity and gas (D–E) are the most GHG intensive sectors of our sample. A decrease in their inputs (supplied by mining) generates large amounts of avoided emissions. In those sectors, the key challenge for forthcoming recovery plans is to ensure a shift from dirty to low-carbon inputs.[47] Starting from the power generation sector, which is among the most emitting industries in some EU countries (i.e. Germany, Poland) and rank top at the regional scale European Environment Agency, 2020, shifting from high to low-carbon technologies has become a major issue over the last years International Renewable Energy Agency, 2018. For instance, the German government recently announced a total phase-out of coal-

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[47] Not only to shift away from mining, but also because mining inputs are expected to be phased-out from the economic system by 2050.

power plants by 2038, compensated by large-scale investments in renewable energy sources (RES) (Reuters, 2020) while the French National Energy Roadmap targets 36% of power generation from renewables in the energy mix by 2028 (Le Monde, 2020). Although official statements might drive sectoral dynamics (e.g. private investments), barriers to the large-scale deployment of RES have remained strong (see Sen & Ganguly, 2017 for a review). Among others, storage capacity issues and energy infrastructures (e.g. cost) have particularly constrained RES expansion (Jones, 2015; Ruz & Pollitt, 2016). In the wake of current public incentives to promote RES deployment (see Solorio & Jorgens, 2017 for a review), forthcoming green stimulus should enlarge the scope of targeted sectors and tackle such barriers (Allan et al., 2020; European Commission, 2020). Measures such as public R&D support and EU cross-border cooperation could target technologies that complement renewables (e.g. energy storage, smart grids, interconnectors). The latter would guarantee that capacity exists to facilitate decarbonisation of further downstream industries too (e.g. mobility and heating).[48]

From an economic perspective, the pandemic is unfolding in a policy environment providing strong advantages to a green design of recovery plans. Indeed, since the global financial crisis (2007–2008) and recovery plans that followed, the cost of low-carbon technologies (e.g. solar, wind) has sharply declined compared to other energy sources, making large-scale financing affordable and competitive (Bloomberg NEF, 2019). Importantly, in the short run, green stimulus measures are economically advantageous when compared with traditional fiscal stimuli (World Resource Institute, 2009), creating higher numbers of jobs (Pollin et al., 2008). In the long run, these public investments offer high returns by driving down costs of the clean energy transition (World Bank, 2015). While unemployment rates in EU economies are predicted to soar in 2020 (Reuters, 2020), such dimensions are critical to consider when shaping green stimulus.

Moving to GHG intensive industries, transforming industrial energy usage is a major issue to handle for governments. In our paper, we have identified coke and refined petroleum products (C19), chemicals (C20–21) as well as basic metals (C24) to have a significant impact on emissions. For those activities, creating incentives to produce low-carbon output would guarantee a slowdown in industrial emissions. The development of programs guaranteeing the purchase of cleaner output at a profitable price could be a first step towards an environmental-friendly shift in production (Allan et al., 2020). In this context, a significant price of carbon (e.g. internal/external carbon tax, EU-ETS market permit) could lead to higher investments in R&D focusing on potential environmental-friendly substitutes (CDP, 2017). In the same way, green stimuli should contain large-scale investments in greenhouse gas removal technologies including industrial carbon capture and storage. These technologies are necessary to contain emissions from heavy polluting

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[48] Note that in some countries, decarbonising the power sector does not come as a priority compared to, for instance, transport sectors (e.g. France).

industries. Although barriers exist (e.g. infrastructures, cost), more research and developments targeting such technologies could bring multiple benefits in the long run (Hepburn et al., 2019). Moreover, if rapidly deployed, such technologies could limit emissions during the transition period towards cleaner production processes in GHG intensive industries.

To conclude, our paper has investigated industries that should not benefit from economic recovery stimuli if EU governments wish to decouple growth and emissions once activity recovers (OECD, 2020). Although the mining sector is identified as the sector at the core of potential emission reductions, GHG intensive activities such as coke and refined petroleum products and power generation activities are likely to act as key sectors to reach a post-carbon society. The ongoing COVID-19 pandemic crisis acts as a stalemate in the fight against climate change as recovery plans will shape the economy for the decades to come. Reaching a carbon neutral European Union by 2050 largely depends on the design of forthcoming recovery packages. Decoupling emissions and economic growth will become possible if identified sectors are phased-out or if they implement strategies to clean their production process. Although we have discussed some potential policy strategies for such changes, the latter is unlikely to happen without a strong support from national and EU Institutions. At the EU regional scale, a major issue to come is the allocation of such recovery funds across states—and further, sectors to benefit from such funds within national economies. In our paper, we have shown that economies display differences in terms of industrial structures and GHG emission levels. The latter calls for different national approaches to tackle GHG emissions. If some countries have a large proportion of mining inputs in the energy mix (e.g. Germany and Poland), a uniform implementation of tools to meet the EU targets would cause heterogeneous impacts across economies, likely reinforcing economic and political divisions within the Union. In the coming months, the EU Commission will have to be aware of such differences when evaluating the effectiveness of recovery plan allocation funds by national states. Whether the supervision of such funds is centralised or decentralised (i.e. EU Institutions or national states), it will have a strong impact on the EU ability to meet its legally mandated environmental targets.

Appendix

See Tables 4, 5, and 6

Additional Information

Description of Sectors

Table 4 NACE sectors

Sector code	Sector description
A	Agriculture, forestry and fishing
B	Mining and Quarrying
C	Manufacturing
D	Electricity, gas, steam and air conditioning
E	Water supply; sewerage; waste management and remediation services
F	Constructions and construction works
G	Wholesale retail trade; repair of motor vehicles and motorcycles
H	Transportation and storage
I	Accommodation and food services activities
J	Information and communication
K	Financial and insurance activities
L	Real estate activities
M	Professional, scientific and technical activities
N	Administrative and support service activities
O	Public administration and defence: compulsory social security
P	Education
Q	Human health and social work activities
R	Arts, entertainment and recreation
S	Other services activities

A—Agriculture, Forestry and Fishing Non-perennial crops; Perennial crops; planting material: live plants, bulbs, tubers and roots, cuttings and slips; mushroom spawn; live animals and animal products; agricultural and animal husbandry services (except veterinary services); hunting and trapping and related services; forest trees and nursery services; wood in the rough; wild growing non-wood products; support services to forestry; fish and other fishing products; aquaculture products; support services to fishing.

B—Mining and Extraction of Energy Producing Products Hard coal; lignite; crude petroleum; natural gas, liquefied or in gaseous state; iron ores; non-ferrous metal ores; stone, sand and clay; mining and quarrying products n.e.c.; support services to petroleum and natural gas extraction; support services to other mining and quarrying.

C10–12—Food Products, Beverages and Tobacco Preserved meat and meat products; processed and preserved fish, crustaceans and molluscs; processed and preserved fruit and vegetables; vegetable and animal oils and fats; dairy products; grain mill products, starches and starch products; bakery and farinaceous products; other food products; prepared animal feeds; beverages; tobacco products.

C13–15—Textiles, Wearing Apparel, Leather and Related Products Textile yarn and thread; woven textiles; textile finishing services; other textiles; wearing apparel,

Table 5 Greenhouse gas emissions (Mt CO_2 eq.) by sectors (A–F), year 2015

Sector	France	Germany	Italy	Poland	Spain
Agriculture, forestry and fishing	90.7	75.8	39.4	44.1	50.0
Mining and extraction of energy producing products	1.1	7.2	4.7	22.0	1.5
Food products, beverages and tobacco	11.0	9.9	6.2	5.1	3.5
Textiles, wearing apparel, leather and related products	0.8	0.9	2.9	0.2	0.8
Wood and of products of wood and cork (except furniture)	0.5	1.0	0.3	0.5	1.4
Paper products and printing	2.8	7.8	5.4	2.4	2.7
Coke and refined petroleum products	14.0	22.2	17.9	12.6	16.1
Chemicals and pharmaceutical products	22.8	30.2	11.8	14	11.5
Rubber and plastics products	1.5	3.2	0.4	0.7	0.0
Other non-metallic mineral products	18.8	36.0	26.2	15.6	28.1
Manufacture of basic metals	19.0	44.7	14.1	9.7	13.8
Fabricated metal products, except machinery and equipment	1.0	3.8	0.8	0.5	0.6
Computer, electronic and optical products	0.4	1.1	0.4	0.1	0.0
Electrical equipment	0.5	1.3	0.5	0.2	0.7
Machinery and equipment n.e.c.	0.6	3.2	1.7	0.2	0.6
Motor vehicles, trailers and semi-trailers	1.0	4.6	0.3	0.3	1.0
Other transport equipment	0.4	0.5	0.0	0.1	0.2
Other manufacturing; repair and installation of machinery and equipment	1.2	1.3	0.8	0.3	0.0
Electricity, gas, water supply, sewerage, waste and remediation services	49.8	363.9	119.0	167.5	88.1
Construction	9.1	11.2	5.9	0.9	0.6

Table 6 GHG emissions (Mt CO_2 eq.), year 2015

Country	GHG emissions
France	330.7
Germany	769.5
Italy	314.2
Poland	341.7
Spain	277.9

except fur apparel; articles of fur; knitted and crocheted apparel; tanned and dressed leather; luggage, handbags, saddlery and harness; dressed and dyed fur; footwear.

C16—Wood and of Products of Wood and Cork (Except Furniture) Wood, sawn and planed; products of wood, cork, straw and plaiting materials

C17–18—Paper Products and Printing Pulp, paper and paperboard; articles of paper and paperboard; printing services and services related to printing; reproduction services of recorded media.

C19—Coke and Refined Petroleum Products Coke oven products; refined petroleum products.

C20–21—Chemicals and Pharmaceutical Products Basic chemicals, fertilisers and nitrogen compounds, plastics and synthetic rubber in primary forms; pesticides and other agrochemical products; paints, varnishes and similar coatings, printing ink and mastics; soap and detergents, cleaning and polishing preparations, perfumes and toilet preparations; other chemical products; man-made fibres; basic pharmaceutical products; pharmaceutical preparations.

C22—Rubber and Plastics Products Rubber products; Plastic products.

C23—Other Non-metallic Mineral Products Glass and glass products; refractory products; clay building materials; other porcelain and ceramic products; cement, lime and plaster; articles of concrete, cement and plaster; cut, shaped and finished stone; other non-metallic mineral products.

C24—Manufacture of Basic Metals Basic iron and steel and ferro-alloys; tubes, pipes, hollow profiles and related fittings, of steel; other products of the first processing of steel; basic precious and other non-ferrous metals; casting services of metals.

C25—Fabricated Metal Products, Except Machinery and Equipment Structural metal products; tanks, reservoirs and containers of metal; steam generators, except central heating hot water boilers; weapons and ammunition; forging, pressing, stamping and roll-forming services of metal; powder metallurgy; treatment and coating services of metals; machining; cutlery, tools and general hardware; other fabricated metal products.

C26—Computer, Electronic and Optical Products Electronic components and boards; computers and peripheral equipment; communication equipment; consumer electronics; measuring, testing and navigating equipment; watches and clocks; irradiation, electromedical and electrotherapeutic equipment; optical instruments and photographic equipment; magnetic and optical media.

C27—Electrical Equipment Electric motors, generators, transformers and electricity distribution and control apparatus; batteries and accumulators; wiring and wiring devices; electric lighting equipment; domestic appliances; other electrical equipment.

C28—Machinery and Equipment n.e.c General-purpose machinery; other general-purpose machinery; agricultural and forestry machinery; metal forming machinery and machine tools Other special-purpose machinery.

C29—Motor Vehicles, Trailers and Semi-Trailers Motor vehicles; bodies (coachwork) for motor vehicles; trailers and semi-trailers; parts and accessories for motor vehicles.

C30—Other Transport Equipment Ships and boats; railway locomotives and rolling stock; air and spacecraft and related machinery; military fighting vehicles; transport equipment n.e.c.

C31–33—Other Manufacturing Furniture; jewellery, bijouterie and related articles; musical instruments; sports goods; games and toys; medical and dental instruments and supplies; manufactured goods n.e.c.; repair services of fabricated metal products, machinery and equipment; installation services of industrial machinery and equipment.

D–E—Electricity, Gas, Water Supply, Sewerage, Waste and Remediation Services Electricity, transmission and distribution services; manufactured gas; distribution services of gaseous fuels through mains; steam and air conditioning supply services; natural water; water treatment and supply services; sewerage services; sewage sludge; waste; waste collection services, waste treatment and disposal services; materials recovery services; secondary raw materials; remediation services and other waste management services.

F—Construction Buildings and building construction works, roads and railways; construction works for roads and railways; constructions and construction works for utility projects; constructions and construction works for other civil engineering projects; demolition and site preparation works; electrical, plumbing and other construction installation works; building completion and finishing works; other specialised construction works.

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Low-Carbon Transition of EU-ETS Firms: Assessing the Long-Term Effects of Covid-19

Marc Baudry

1 Introduction

During spring 2020, some collateral effects of Covid-19 on the environment were highly publicised. Views of large Chinese metropolises, under an unusual blue sky totally free of smog, were widely circulated, as well as videos of wild animals moving fearlessly in the middle of avenues free from automobile traffic. Some saw it as the sign of a shift towards a new carbon-free era. Others, more pessimistic, stressed that appearances can be misleading: was it not the basic result of a sharp and generalised decline in activity, and the premises of an economic crisis doubling the health crisis and which could lead to delaying efforts to invest in low-carbon solutions? This is the question this chapter seeks to answer by analysing in particular the potential long-term effects of the Covid-19 crisis on the European Union Emission Trading System (EU-ETS). The guiding line of the chapter is that, even if the cap on emissions remains unchanged and respected, the economic crisis induced by the Covid-19 health crisis could result in a lower decarbonation of the economy due to a decrease in investments in "green" capital. For this purpose, it builds on the dynamic modelling of an emissions permit market.

The idea of regulating pollution problems through an emissions permit market dates back at least to Dales (1968) and Montgomery (1972). Well known today to environmental economists, its static analysis points to the interest of allowing the trading of permits to minimise compliance costs, which is referred to as spatial flexibility (Fankhauser & Hepburn, 2010b). It is only more recently that the concept known as temporal flexibility (Fankhauser & Hepburn, 2010a) has been investigated. Temporal flexibility corresponds to the fact that a firm covered by an

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emissions allowance market can borrow or bank permits in order to minimise its discounted sum of compliance costs. It has been analysed by Rubin (1996) and Cronshaw and Kruse (1996) in the context of a pollution damage generated by the emission flow, and then extended to the case of a pollution damage that may depend on the pollution stock by Leiby and Rubin (2001). In the resulting dynamic approach to emissions allowance markets, the absence of arbitrage opportunities plays a central role for the determination of the intertemporal equilibrium in a manner akin to the well-known Hotelling's rule in natural resource economics. Despite it takes into account intertemporal choices, this approach should be designated as medium term rather than long term. Indeed, it is generally based on the assumption of an abatement cost function which is time invariant.

A noticeable exception is the article by Kling and Rubin (1997) which highlights how the prospect of higher marginal abatement costs over time may encourage more short-term abatements and induce banking of the amount of allowances thus released for use in the long term. However, Kling and Rubin (1997) do not explain the mechanisms at work in the modification of the abatement cost function over time. Similarly, Phaneuf and Requate (2002) consider the interplay between abatement decisions and investment decision, but they postulate rather than demonstrate that low-carbon investments reduce both the total abatement and the marginal abatement costs. When dealing with investment in low-carbon solutions, more recent research works either assume that investments are made in capital specifically devoted to abatement (Saltari & Travaglini, 2011; Pommeret & Schubert, 2018) or in the form of irreversible abatements (Slechten, 2013). Only a few authors seem to have studied either theoretically (Bréchet & Jouvet, 2008) or empirically (Calel, 2020; Baudry & Faure, 2021) the role of innovation, technological change or investment in low-carbon solutions on the deformation of the marginal abatement curve over time. This chapter fills the gap and puts the emphasis on the key role played by investments in low-carbon capital in changes affecting the abatement cost curve.

The chapter is organised as follows. The first section presents stylised facts to highlight factors that seem to affect the EU-ETS price dynamics. The first attempt to compare the reaction of this price to the subprime crisis of 2008 and to that of the Covid-19 is proposed. It emerges from stylised facts that the price dynamics is likely to be influenced by demand shocks on the market for goods produced by firms subject to the EU-ETS regulation, but is also probably influenced by price variations of fossil fuels as well as investments in low-carbon solutions. The second section explains the construction of the abatement cost curve. Capital heterogeneity is more specifically introduced. It makes it possible to integrate into the model the fact that the combination of a quantity of energy with a quantity of capital does not produce the same level of CO_2 equivalent emissions depending on the type of capital used. By introducing in this way the concept of "green" capital and "brown" capital, it is shown how the abatement curve changes according to the investments made. In particular, it is outlined that the substitution of "green" capital for "brown" capital tends to reduce baseline emissions but increases the marginal abatement cost. The intertemporal behaviour of firms and the dynamic equilibrium of the emissions permit market are respectively detailed in the third and fourth sections. The modelling approach includes both spatial and temporal flexibility as well as the existence of compliance dates before the statutory end date of the market is reached. The fifth section details how the model is calibrated on real data from the EU-ETS. Finally, the sixth section presents a prospective analysis of the effects of the Covid-19 crisis on the dynamics of the EU-ETS through simulations. This section does not claim to produce estimates of these effects but rather seeks to assess whether the Covid-19 crisis is likely to accelerate or on the contrary delay the transition to a low-carbon economy. For this purpose, particular attention is paid in the simulations to the results relating to the evolution of “green” and “brown” capital stocks.

2 Stylised Facts

The subprime crisis that began in 2008 and the Covid-19 crisis that occurred in March 2020 for Europe are the two major macroeconomic shocks suffered by the EU-ETS over its 15 years of existence. The dynamics of the price of allowances around these two shocks are however very contrasted. While the price of allowances had permanently halved after the subprime crisis, from a value of around 28 euros per tonne of CO_2 in summer 2008 to a value of around 15 euros per tonne of CO_2 from January 2019 to September 2011, the drop following the Covid-19 crisis has been less, and, above all, it seems purely transitory. In March 2020, the price fell from 23 euros per tonne of CO_2 at the beginning of the month to 15.24 euros per tonne of CO_2 on March 18, but from the end of June 2020 the price again exceeded 25 euros per tonne of CO_2 without ever falling significantly since. Figure 1 visualises the impact of these two crises on the price of allowances over a period of 1 year, roughly centred on its paroxysm—as regards the EU-ETS—for each crisis (from June 2008 to June 2009 for the subprime crisis and from November 2019 to November 2020 for the Covid-19 crisis). The contrast between the two crises is emphasised by the fact that the starting level of the price of allowances was relatively close.

Figure 2 completes the comparison by showing the time series of the spot prices from the beginning of the EU-ETS phase II in January 2008 until February 2021. The spot prices of phase I are not shown because, due to the conjunction of the impossibility of postponing the use of allowances from this specific phase to the next one and the observation that the granting of allowances had been too generous, a drastic drop in the spot price occurred at the end of this phase. Figure 2 clearly shows that the Covid-19 crisis has had only a one-off impact on a markedly upward price trajectory since spring 2018. The price even reached its highest level, at almost 40 euros per tonne of CO_2, after the Covid-19 crisis.

This graphical comparison has its limits, however. First of all, the long period of price depression covering the years 2012–2017 is not attributable to the 2008 subprime crisis alone. The academic literature has, among other causes, documented how the massive support for renewable energies introduced in European countries

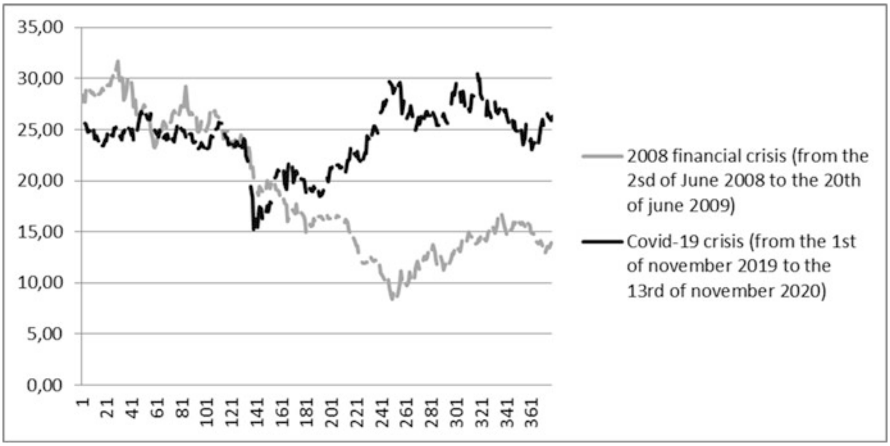

Fig. 1 Comparison of the daily price of allowances (in euros per tonne of CO_2) during the 2008 financial crisis and during the Covid-19 crisis. (Source: https://ember-climate.org/data/carbon-price-viewer/ reworked by the author)

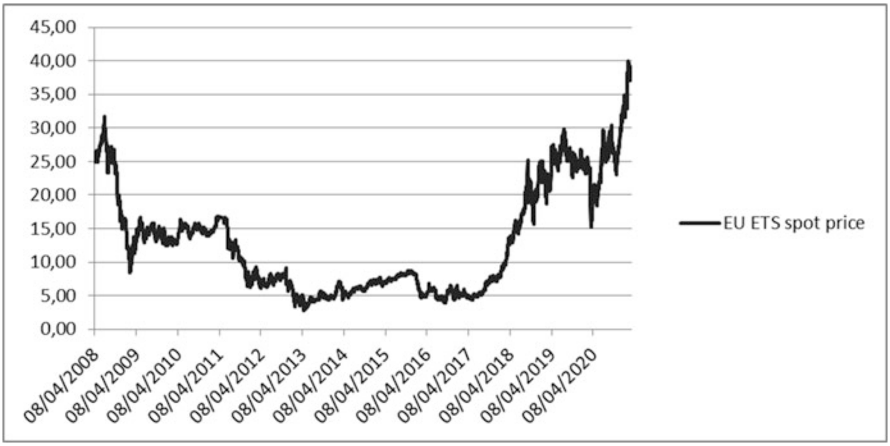

Fig. 2 Time path of the daily price of allowances (in euros per tonne of CO_2) from April 2008 to February 2021. (Source: https://ember-climate.org/data/carbon-price-viewer/ reworked by the author)

over the same period contributed to reducing the demand for emission allowances by the electric power sector (Koch et al., 2014). More generally, the economic context was not the same. The first major difference is that the subprime crisis had an economic origin and that, as a result, the economic fundamentals were permanently affected. Conversely, the Covid-19 crisis has a health origin unrelated to the economic situation that prevailed just before it occurred. Even if, at the time of the onset of the crisis, the fall in activity was stronger with Covid-19, it is quite possible that economic players are considering a better capacity for recovery compared to the subprime crisis. More generally, it is necessary to take into account the determinants of the price of emission allowances to get an idea of the long-term effects of the Covid-19 crisis on the EU-ETS.

For a permit market like the EU-ETS, created to correct an environmental externality by imposing a quantitative limit on emissions, the price is intrinsically very dependent on the degree of ambition and the credibility of the environmental commitments of public policies. From this point of view, two policy measures seem to be of interest. The first one is the short-term measure known as "back-loading" implemented from 2014. The second one is the more structural and long-term measure constituted by the "Market Stability Reserve" which just took over "back-loading" and entered into force in 2019. Both seem to have brought a credible response to the overabundance of quotas linked to initially too generous allocations, to contradictory policies such as the direct financial support for renewable energies already mentioned, and to the depression of the demand for quotas induced by the 2008 crisis. The increase, barely disturbed by the Covid-19 crisis, in the price of emission allowances since 2018 can thus be seen as the result of a market at least in part freed from its youthful anomalies. According to this reading, the signal of scarcity of emission rights would have become the main determinant of the price, in accordance with what is highlighted by the economic modelling of this type of market in dynamics, in particular Hotelling's rule applied to this particular type of asset. This signal is however disturbed by variations in the level of activity of the sectors covered by the EU-ETS. As a result, the price of emission allowances is expected to fluctuate with economic indicators of the business cycle. Figure 3 aims at illustrating this influence by superposing the dynamics of the monthly average price of allowances and that of the Purchasing Managers' Index (PMI) of manufacturing sectors for Europe. Figure 3 highlights that the shock of the 2008 subprime crisis was only relatively temporary in terms of the business cycle but much more lasting for the price of allowances. On the one hand, the long phase of quota price depression between years 2011 and 2017 is clearly not explained by the business cycle. Conversely, the sharp rise in the price of allowances that started in 2017 goes against the deterioration observed for the PMI until the Covid-19 crisis. On the other hand, the two curves seem to be affected only temporarily by the shock of Covid-19, the post-Covid-19 recovery being clear in both cases.

Another explanatory factor for the price of emission allowances is likely to play an important role in the difference in the price trajectory following the subprime crisis and the Covid-19 crisis: the price of oil. The influence of this factor is however more complex because it acts through several channels. First of all, the price of oil interferes with the price of allowances through decisions to switch between different fossil fuels by sectors subject to the EU-ETS, particularly the electric power sector. More precisely, the price of oil impacts the price of gas which tends to vary in the same direction, and it is gas which can be substituted for coal in the production of electricity. Creti et al. (2012) thus find a positive cointegration relationship between the price of the barrel of Brent and the price of emission allowances futures during phase I and phase II of the EU-ETS. As will appear *infra*, such a switching opportunity affects the baseline emissions and the marginal abatement cost curves.

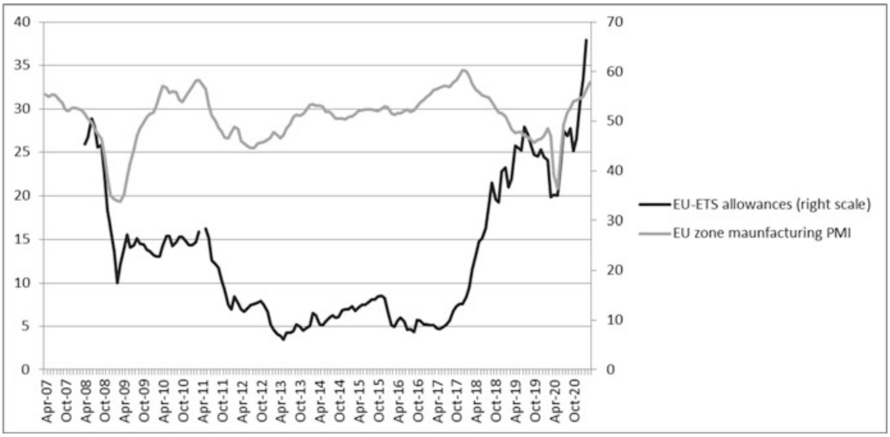

Fig. 3 Comparison of the dynamics of the monthly average spot price of EUA futures (left scale, in euros per tonne of CO_2) and the time path of the manufacturing PMI for Europe (right scale). (Source: https://ember-climate.org/data/carbon-price-viewer/ reworked by the author and https://www.mql5.com/en/economic-calendar/european-union/markit-manufacturing-pmi)

Beyond this partially reversible substitution effect, the price of oil is also likely to guide investment decisions over the long term. This effect is however difficult to quantify because, ideally, this would require statistical information on the types of capital in which the firms covered by the EU-ETS invest. Following Aghion et al. (2016), patent filings in low-carbon technological fields can serve as a proxy variable to assess this effect.

The Cooperative Patent Classification (CPC) proposes a reclassification of all patents according to the Y02 class (and its subclasses) covering a wide range of technologies for mitigation or adaptation against climate change. In accordance with the literature dealing with induced technical progress (Acemoglu et al., 2012), the R&D effort is supposed to respond to economic signals on the profitability of different types of innovation, in particular innovation in "green" rather than "brown" technologies. In turn, this profitability depends on the demand for the different types of capital, in particular investments in capital allowing to reduce greenhouse gas emissions and/or to improve the energy efficiency of production processes. Following this idea, Fig. 4a compares, on the one hand, the evolution of the price of a barrel of Brent and, on the other hand, the ratio between patents filed at the European Patent Office (EPO) and which relate to at least one of the Y02 classes or subclasses of the CPC and fillings of patents without any Y02 class. Rather than counting these patents, the ratio between the two subsets of patents is used in order to avoid a bias linked to the sharp development of patent filings for all technologies taken as a whole. Figure 4a suggests a positive correlation between low-carbon innovation and the price of Brent up to 2012. However, the decline in the share of low-carbon patents from 2012 took place before the drop in the price of Brent. Completing Fig. 4a with Fig. 4b, it does not seem unreasonable to argue that

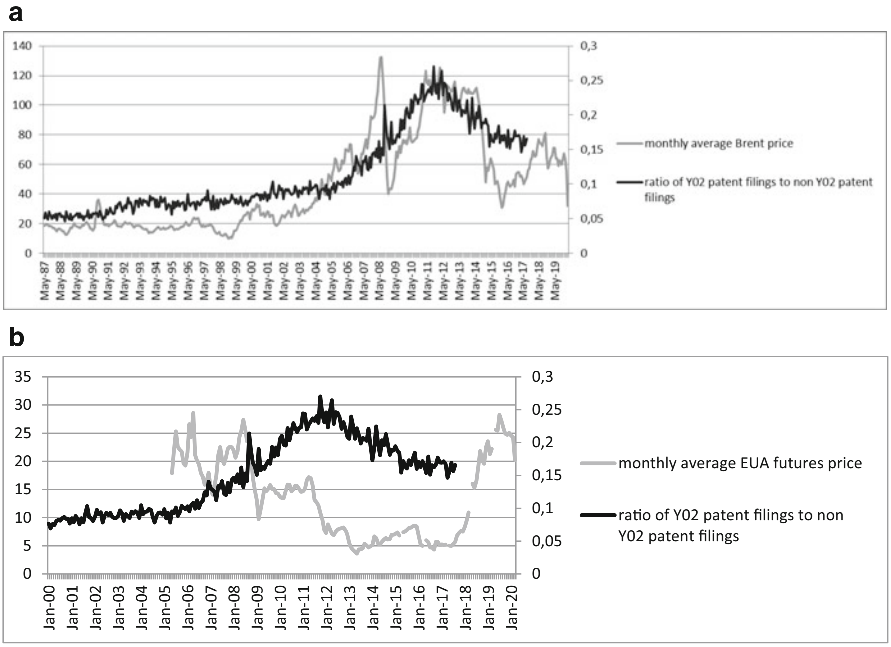

Fig. 4 (**a**) Comparison of the dynamics of the monthly average price of Brent (left scale, in dollars per barrel) and the time path of the ratio between patent filings at the EPO referring to at least one Y02 CPC class and patent filings at the EPO that do not refer to the Y02 CPC classes (right scale) (source: Patstat (extraction and formatting by the author) and https://www.eia.gov/petroleum/data.php#prices reworked by the author). (**b**) Comparison of the dynamics of the monthly average price of EUA futures (left scale, in euros per tonne) and the time path of the ratio between patent filings at the EPO referring to at least one Y02 CPC class and patent filings at the EPO that do not refer to the Y02 CPC classes (right scale). (Source: Patstat (extraction and formatting by the author) and https://www.quandl.com/search?query=ECX+EUA+Futures%2C+Continuous+Contract&redirect=true reworked by the author)

the decline in the share of low-carbon patents has at least partly resulted from the fall in the price of CO_2 emission allowances, with a relatively large time lag that can be explained by the time required between the decisions to launch a R&D program and the realisation of its result in the form of patent filing. The positive relationship between the implementation of the EU-ETS and the filing of low-carbon patents highlighted by Calel and Dechezleprêtre (2016) supports this interpretation. The test developed by these authors however relates only to the effect of the implementation of the EU-ETS, not the effect of its price variations and magnitude.

The complex interactions that seem to appear between the price of Brent, the price of emission allowances and low-carbon investments call for these investment decisions to be taken into account in order to better assess the long-term effects of the Covid-19 crisis and to disentangle, among the effects currently observed, those which relate to short-term adjustments and those which relate to a long-term trend. This is what the following sections propose.

3 Abatement Costs Modelling

In what follows, we wish to develop a modelling of the possibility, for companies emitting greenhouse gases and covered by the EU-ETS, to go beyond the flexibility introduced by the possibility of trading or banking quotas, namely their ability to make low-carbon investments that have a lasting impact on their emissions. To achieve this goal, it is necessary to consider that capital is heterogeneous in terms of the level of emissions achieved for given levels of production inputs. The link between the abatement cost function and the different types of capital must also be clarified.

Each emitter i is supposed to be able to produce with M different types of capital in quantity k_{mi} ($m \in \{1, \ldots, M\}$). Each type of capital corresponds to a different production function, in the same spirit as the so-called capital generation models. In addition to capital, production requires energy e_{mi} which generates more or less greenhouse gas emissions, depending on the type of capital with which it is combined. In what follows, the heterogeneity between types of capital relates only to the level of emissions generated when combined with energy so that these different types can be ranked on an environmental performance scale ranging from very polluting or "brown" capital to low emitting or "green" capital. Labour is not explicitly taken into account or, equivalently, it is postulated that there is perfect complementarity between labour and energy. In order to make it easier to obtain the abatement cost function, and subsequently to facilitate the analysis of market dynamics, the functional form retained for each production function is the following constant return to scale production function

$$y_{mi} = A\sqrt{k_{mi}\ e_{mi}} \tag{1}$$

where A is a productivity parameter and y_{mi} denotes the level of output obtained with capital of type m. The level of emissions generated is proportional to the level of production but depends on the type of capital used. This level is defined by the relation

$$u_{mi} = \theta_m\ y_{mi} \tag{2}$$

with θ_m the carbon intensity of the production process relying on the type of capital m. A low (resp. high) value of θ_m is associated with a "green" (resp. "brown") type of capital. The output produced with the different types of capital is homogeneous and sold under conditions of pure and perfect competition at price p_y. Likewise, the energy used is homogeneous and purchased at an exogenous price noted as p_e. In the short term, i.e. with a given stock of the different types of capital, each emitter seeks to maximise its profit under the constraint of not exceeding a total level of emissions y_{mi}:

$$\max_{\{e_{i1},\ldots,e_{iM}\}} p_y A \sum_{m=1}^{M} \sqrt{k_{mi} e_{mi}} - p_e \sum_{m=1}^{M} e_{mi} \tag{3a}$$

$$\text{s.t.} \quad \sum_{m=1}^{M} u_{mi} \leq q_i \tag{3b}$$

where the emission levels u_{mi} are linked to capital and energy as described in Eqs. (2) and (1). The only source of heterogeneity between the different production processes and types of capital is their carbon intensity. However, the constraint on the total level of emissions that the firm seeks not to exceed does not lead it to use only the least polluting type of capital. Indeed, it must balance the fact that this production process is less polluting with the fact that, in virtue of the law of diminishing marginal returns, increasing the corresponding level of production implies a decrease in marginal productivity. We note from the outset that the productivity parameter A and the output price p_y always appear in a multiplicative form. Without loss of generality, we thus set $A = 1$. In addition, it can be checked that the short-term profit maximisation induces that the emission constraint is bidding. Letting ϑ_i denote the Lagrange multiplier associated with this constraint, the short-term maximisation program of an emitter i in the absence of an emissions allowance market may be written as

$$\max_{\{e_{i1},\ldots,e_{iM}\}} p_y \sum_{m=1}^{M} \sqrt{k_{mi} e_{mi}} - p_e \sum_{m=1}^{M} e_{mi} - \vartheta_i \left(\sum_{m=1}^{M} \theta_m \sqrt{k_{mi} e_{mi}} - q_i \right) \tag{4}$$

The first-order condition for the maximisation with respect to the energy used jointly with each type of capital yields the optimal emission level associated with type m of capital

$$u_{mi} = u_{mi}^{\text{free}} - \frac{1}{2} \frac{\vartheta_i}{p_e} \theta_m^2 k_{mi} \tag{5a}$$

with

$$u_{mi}^{\text{free}} = \frac{1}{2} \frac{p_y}{p_e} \theta_m k_{mi} \tag{5b}$$

the *laissez-faire* (or baseline) emission level obtained in the absence of constraint on the total level of emissions. Equation (5a) thus explicitly shows how the constraint leads to reducing the level of emissions resulting from the use of each type of capital, in a differentiated manner according with the value of the carbon intensity coefficient θ_m. By substituting Eqs. (5a) and (5b) in the total emissions constraint, and after some rearrangements, the implicit price ϑ_i of emissions for emitter i is obtained:

$$\vartheta_i = 2\frac{p_e}{\sum_{m=1}^{M} \theta_m^2 k_{mi}} a_i \tag{6}$$

where $a_i = \sum_{m=1}^{M} u_{mi}^{\text{free}} - q_i$ is the total level of abatement implemented by emitter i and defined as the reduction of the total emission level compared to the *laissez-faire* situation. By substituting these solutions in the expression of profit (Eq. 3a), the optimal short-term profit with abatement may be written as

$$\pi_i\left(a_i\right) = \pi_i^{\text{free}} - \frac{p_e}{\sum_{m=1}^{M} \theta_m^2 k_m} a_i^2 \tag{7a}$$

with

$$\pi_i^{\text{free}} = \frac{p_y^2}{4\ p_e} \sum_{m=1}^{M} k_{mi} \tag{7b}$$

the profit level under *laissez-faire*. The last term in Eq. (7a) is the abatement cost function. It has the usual quadratic form with respect to the level of abatement, which reveals to be quite convenient for the dynamic programming approach of the intertemporal analysis of the EU-ETS. The marginal abatement cost is also the implicit price of emissions defined in Eq. (6). Beyond its usual quadratic form in the abatement level, the abatement cost as modelled here exhibits several important properties for the long-term dynamics of the market.

First, the slope of the marginal abatement cost is proportional to the price of energy p_e. A drop in the price of energy, assimilated in the rest of the chapter to a drop in the price of a barrel of Brent, implies that an unchanged level of abatement is associated with a lower marginal cost of abatement. Equivalently, but provided that in the dynamic analysis the marginal abatement cost and the market price of emission allowances are closely linked, a same level of the price of allowances will induce a higher level of abatement if the energy prices fall. A drop in the price of energy has thus two consequences in the short term. The first consequence is an increase in the baseline emission level, as indicated by Eq. (5b), whatever the type of capital considered. The second consequence is a decrease in the marginal cost of abatement. The net effect of these two opposite consequences is given by Eq. (5a). Assuming that the emission level is positive, this net effect is also positive. Nevertheless, its magnitude depends on the output price p_y and the carbon intensity coefficient θ_m of the different production processes. Hence, this result calls for distinguishing between sectors when analysing the impact of the price of energy on the EU-ETS. Note that the price p_y of the output acts in a much simpler way on the short-term choices of the firm. This price acts upwards on the baseline emissions but has no impact on the marginal abatement cost.

Second, the slope of the marginal abatement cost depends on the composition of capital. For the same total level of capital, the higher the share of "brown" capital the lower is the slope of the marginal abatement cost. A "green" investment strategy comes at the expense of more costly abatements. *Ceteris paribus* "green" investment therefore induces a lasting reduction in emissions but makes additional abatement efforts more expensive.

The effect of energy prices and the effect of capital composition are likely to be closely intertwined in the analysis of the dynamics of the emissions allowance market. In addition to the fact that both act simultaneously on baseline emissions and on the marginal abatement cost, one should expect that the price of energy will also guide investment choices in the long run. Indeed, once the price of energy is a determinant of the price of emission allowances, it has an indirect effect on investment choices. This is what the following section seeks to highlight through the dynamic analysis of the EU-ETS.

4 Intertemporal Behaviour of Firms

It is assumed that the market operates with the possibility of banking allowances at each date t until the time horizon T known to all and corresponding to the end of the market.[1] Each emitting firm i receives on dates $t \in \{0, \ldots, T\}$ a quantity q_{it} of emission allowances which may be zero for some dates. The idea is that, for example, firms receive at some dates (typically once a year) quotas but nothing between these dates (the model is then both intra-annual and inter-annual). It is also assumed that there exists compliance dates (at least once a year) at which firms have to surrender as many allowances as the level of CO_2 they have emitted since the previous compliance date. Firms cannot be short of allowances at compliance dates but may be short during the period separating compliance dates. Said another way, borrowing is allowed on the period separating two consecutive compliance dates but not between two dates separated by a compliance date. Such assumptions are consistent with the rules of the EU-ETS. The modelling approach thus follows Holland and Moore (2013) and Hasegawa and Salant (2014) who stress that, in practice, emissions permit markets do not require firms to surrender permits on a continual basis.

Let b_{it} denote the amount of banking by firm i at the beginning of period t (it is negative in the case of borrowing), x_{it} denote the net purchases of allowances by firm i at period t (it is positive if the firm is a net buyer and negative if the firm is a net seller). Recall that a_{it} and u_{it}^{free} are respectively the abatement level and the baseline emissions of firm i at period t. Moreover, u_{it}^{free} is defined as the sum of

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[1] All firms are assumed to plan their intertemporal decisions from the current date up to the same time horizon which corresponds to the statutory end date of the market. Rolling horizon (Quemin & Trotignon, 2021) is not considered.

baseline emissions resulting from the different types of capital given by Eq. (5b). The dynamics of banking is defined by the following relation:

$$b_{it+1} = b_{it} - u_{it}^{\text{free}} + q_{it} + x_{it} + a_{it} \tag{8}$$

All firms are price takers. There is a transaction cost $\frac{\gamma_i}{2} {x_{it}}^2$ which is symmetric and quadratic with respect to the net amount of traded allowances. The transaction cost parameter γ_i may differ from one firm to another. Another source of heterogeneity between firms lies in the discount rate ρ_i which can be interpreted as a Weighted Average Cost of Capital (WACC) and indirectly captures issues of asymmetry of information on the credit market. In parallel, the dynamics of the stock of each type of capital is defined by the following relation:

$$k_{mit+1} = k_{mit}\,(1 - \eta_m) + I_{mit} \tag{9}$$

where η_m stands for the depreciation rate and I_{mit} is the level of gross investment in type m of capital by firm i during period t. The price of one unit of capital of type m at date t is p_{kmt}. Firms are also price takers on the markets for the different types of capital. In addition to the market value of newly installed units of capital, investment implies an adjustment cost of the stock of capital which takes the quadratic form $\frac{\delta_{mi}}{2} {I_{mit}}^2$.

Each firm maximises the discounted sum of its profits net of costs relating to the emissions allowance market. At any date $t \in \{0, \ldots, T-1\}$, the behaviour of a firm i can be described using dynamic programming as follows:

$$F_{it}^{*}\left(p_t, b_{it}, k_{1it}, \cdots, k_{Mit}\right) = \underset{\left\{\substack{a_{it}, x_{it}, b_{it+1}, I_{1it}, \ldots, I_{Mit} \\ k_{1it+1}, \ldots, k_{Mit+1}}\right\}}{\text{Max}} \left\{F_{it}\left(p_t, b_{it}, k_{1it}, \ldots, k_{Mit}\right)\right\}$$

where

$$\begin{aligned} F_{it}\left(p_t, b_{it}, k_{1it}, \ldots, k_{Mit}\right) = {} & \pi_i\left(a_i\right) - p_t x_{it} - \tfrac{\gamma_i}{2} {x_{it}}^2 - \sum_{m=1}^{M} p_{kmt}\, I_{mit} - \tfrac{\delta_{mi}}{2} {I_{mit}}^2 \\ & + \lambda_{it}\left(-b_{it+1} + b_{it} + q_{it} - u_{it}^{\text{free}} + x_{it} + a_{it}\right) \\ & + \mu_{it} z_t \left(b_{it} + q_{it} - u_{it}^{\text{free}} + x_{it} + a_{it}\right) \\ & + \sum_{m=1}^{M} \varphi_{mit}\left(-k_{mit+1} + k_{mit}\,(1 - \eta_m) + I_{mit}\right) \\ & + \tfrac{1}{1+\rho_i} F_{it+1}^{*}\left(p_{t+1}, b_{it+1}, k_{1it+1}, \ldots, k_{Mit+1}\right) \end{aligned}$$

and $\pi_i(a_i)$ is the profit function defined in Eqs. (7a) and (7b). The additional condition $I_{mit} \geq 0 \;\forall\, m$ is also introduced. λ_{it} is the (positive) Lagrange multiplier associated with the dynamics of banking, whereas φ_{mit} is the (positive) Lagrange multiplier associated with the dynamics of type m of capital. z_t is an exogenous variable taken value 1 if t is a compliance date and 0 otherwise. μ_{it} is the (non-negative) multiplier associated with the Karush–Kuhn–Tucker conditions stating that banking has to be non-negative at compliance dates:

$$\mu_{it}\left(b_{it}+q_{it}-u_{it}^{\text{free}}+x_{it}+a_{it}\right)=0 \quad \text{with} \quad \mu_{it}\geq 0 \tag{10}$$

In addition to Eqs. (8)–(10), the optimal choice of firm i is characterised by the following first-order conditions of the dynamic program:

$$\frac{\partial F_{it}\left(p_t,b_{it},k_{1it},\ldots,k_{Mit}\right)}{\partial a_{it}}=0 \iff a_{it}=\frac{\lambda_{it}}{c_{it}}+\frac{\mu_{it}z_t}{c_{it}} \quad \text{with} \quad c_{it}=\frac{2p_{et}}{\sum\limits_{m=1}^{M}\theta_m^2 k_{mit}} \tag{11}$$

$$\frac{\partial F_{it}\left(p_t,b_{it},k_{1it},\ldots,k_{Mit}\right)}{\partial x_{it}}=0 \iff x_{it}=\frac{\lambda_{it}-p_t}{\gamma_i}+\frac{\mu_{it}z_t}{\gamma_i} \tag{12}$$

$$\frac{\partial F_{it}\left(p_t,b_{it},k_{1it},\ldots,k_{Mit}\right)}{\partial b_{it+1}}=0 \iff \lambda_{it}=\frac{1}{1+\rho_i}\frac{\partial\ F_{it+1}^{*}\left(p_{t+1},b_{it+1},k_{1it+1},\ldots,k_{Mit+1}\right)}{\partial b_{it+1}} \tag{13}$$

$$\frac{\partial F_{it}\left(p_t,b_{it},k_{1it},\ldots,k_{Mit}\right)}{\partial I_{mit}}=0 \iff I_{mit}=\frac{\varphi_{mit}-p_{mt}}{\delta_{mi}} \quad \forall m\in\{1,\ldots,M\} \tag{14}$$

$$\frac{\partial F_{it}\left(p_t,b_{it},k_{1it},\ldots,k_{Mit}\right)}{\partial k_{mit+1}}=0 \iff \varphi_{mit} = \frac{1}{1+\rho_i}\frac{\partial\ F_{it+1}^{*}\left(p_{t+1},b_{it+1},k_{1it+1},\ldots,k_{Mit+1}\right)}{\partial k_{mit+1}} \quad \forall m\in\{1,\ldots,M\} \tag{15}$$

In Eqs. (11) and (12), the last term involving $\mu_{it}z_t$ indicates that there is respectively an excess abatement and an excess net purchase of emission allowances when the non-negative banking constraint is bidding at a compliance date. Substitution of Eqs. (11) and (12) in the dynamic relation (Eq. 8) with $b_{it+1}=0$ then yields the increment μ_{it} of the implicit price of allowances that make the firm just comply with the non-negative banking constraint. Equation (11) states that it is not the market price of allowances that directly drives abatement decisions but their implicit price for the firm. Equation (12) highlights that in the case of a discrepancy between the two prices, the firm will be either in a long position (if its implicit price exceeds the market price) or a short position (if its implicit price is less than the market price) on the market for allowances. Moreover, the envelop theorem implies that

$$\frac{\partial F_{it}^{*}\left(p_t, b_{it}, k_{1it}, \ldots, k_{Mit}\right)}{\partial b_{it}} = \lambda_{it} \tag{16}$$

Combining Eqs. (13) and (16) yields the dynamics of the implicit price of allowances for firm i:

$$\lambda_{it} = \frac{1}{1+\rho_i}\lambda_{it+1} \tag{17}$$

This is equivalent to Hotelling's rule applied to allowances at the firm level. Similarly, the envelop theorem applied to the stock of each type m of capital yields

$$\frac{\partial F_{it}^{*}\left(p_t, b_{it}, k_{1it}, \ldots, k_{Mit}\right)}{\partial k_{mit}} = \frac{p_{yt}^2}{4p_{et}} + \frac{p_{et}\theta_m^2}{\left(\sum\limits_{m=1}^{M} \theta_m^2 k_{mit}\right)^2} a_{it}^2 - \left(\lambda_{it} + \mu_{it} z_t\right)\frac{p_{yt}}{4p_{et}}\theta_m + \varphi_{mit}\left(1-\eta_m\right) \tag{18}$$

Combining Eq. (18) with Eqs. (14) and (11) yields the optimal investment rule in each type of capital as a function of the price of output, the price of energy, the price of the type of capital and the implicit price of allowances:

$$I_{mit} = \frac{p_{kmt}\left(1-\eta_m\right) - p_{kmt-1}\left(1+\rho_i\right) + \frac{\left(p_{yt} - \left(\lambda_{it}+\mu_{it} z_t\right)\theta_m\right)^2}{4p_{et}}}{\delta\left(1-\eta_m\right)} \quad \text{if positive and 0 otherwise} \tag{19}$$

Going back to expressions (5a) and (5b) of emissions levels, according to the optimal abatement rule (Eq. 11) and expression (6), the short-term implicit price of allowances ϑ_i coincides with the long-term implicit price $\lambda_{it} + \mu_{it} z_t$ resulting from the intertemporal profit maximisation. As a result, the assumption of positive emissions generated by the production process relying on capital of type m comes with the assumption that $p_{yt} - (\lambda_{it} + \mu_{it} z_t)\theta_m > 0$. It follows on that *ceteris paribus* the optimal investment level defined in Eq. (19) is lower for polluting types of capital (high value of θ_m) than for environment friendly types of capital (low value of θ_m). It also follows on that an increase in p_{yt} (resp. p_{et}) induces *ceteris paribus* an increase (resp. decrease) in investment for all types of capital.

5 End of the Market Equilibrium

The analysis of equilibrium at the end of the market deserves a special attention because it substantially affects the whole dynamics of the market. The specificity of the final date of existence of the market is that firms have no longer the possibility to bank allowances or, at least it is worthless banking allowances. Nonetheless, equilibrium at this final date T cannot be solved as the textbook static equilibrium of a permit market due to the existence of transaction costs. Indeed, transaction costs imply that firms are not able to buy and sell as many allowances as they would do if the market was frictionless. As a result, they may bank an excess of allowances at any date before the end of the market. Similarly, they may decide not to sell all allowances they have banked at the final date T if the revenue that would accrue from selling the allowances they have banked was lower than the implied transaction cost. Finally, there is no point investing in less polluting capital at the end of the market because there is no private pecuniary return on this type of investment. Consequently, the behaviour of a firm i at date T can be described by the following program:

$$\max_{\{a_{iT},\, x_{iT}\}} \left\{\pi_{iT}\left(a_{iT}\right) - p_T x_{iT} - \tfrac{\gamma_i}{2} {x_{iT}}^2\right\} \tag{20}$$

under the Karush–Kuhn–Tucker conditions stating that banking has to be non-negative:

$$\mu_{iT}\left(b_{iT} + q_{iT} - u_{iT}^{\text{free}} + x_{iT} + a_{iT}\right) = 0 \quad \text{with} \quad \mu_{it} \geq 0 \tag{21}$$

Condition (21) plays the role of a transversality condition. It implies that either all allowances are sold out at the final date and their implicit price μ_{it} is strictly positive or a share of allowances is kept in bank due to transaction costs and the implicit price of allowances for firm equals zero. Optimal abatement decision and selling or buying decisions associated with this program are identical to Eqs. (11) and (12) except that the implicit price of allowances for firm i is exclusively determined by μ_{iT}, whereas $\lambda_{iT} = 0$. Therefore, the implicit price for firm i at date T is given by

$$\mu_{iT} = \text{Max}\left\{\frac{\frac{1}{\gamma_i}}{\frac{1}{\gamma_i} + \frac{1}{c_{iT}}} p_T + \frac{1}{\frac{1}{\gamma_i} + \frac{1}{c_{iT}}}\left(u_{iT}^{\text{free}} - q_{iT} - b_{iT}\right), 0\right\} \tag{22}$$

Thereafter, the focus is on the case where the implicit price is positive for all firms. Market clearing at date T implies that the net demand for allowances is cancelled out. This net demand is the sum of the net purchases of allowances by the N emitting firms covered by the permit market minus the exogenous supply of allowances Q_T, which results from the auctioning of allowances by the market regulatory authority and/or offsets. This exogenous supply is assumed to be deterministic. The market clearing condition is therefore written as:

$$\sum_{i=1}^{N} x_{iT} - Q_T = 0 \tag{23}$$

By substituting for the net purchases of each firm their optimal expression according to the first-order condition associated with Eq. (20), and then substituting the non-zero solution given by Eq. (22) for μ_{iT}, the following equilibrium market price of allowances is obtained:

$$p_T = \frac{1}{\sum_{i=1}^{N} \frac{\frac{1}{\gamma_i}\frac{1}{c_{iT}}}{\frac{1}{\gamma_i}+\frac{1}{c_{iT}}}} \left(\sum_{i=1}^{N} \frac{u_{iT}^{\text{free}} - q_{iT} - b_{iT}}{\frac{1}{\gamma_i} + \frac{1}{c_{iT}}} - Q_T \right) \tag{24}$$

This final price depends on the level of banking b_{iT} of each firm at the end of the market and, thus, on all previous decisions. We now turn to the analysis of equilibrium at any date t prior to the final date T.

6 Dynamic Market Equilibrium

As at the end date, the market clearing for any earlier date $t < T$ implies that the net demand of allowances equals zero. The net demand is the sum of the net purchases of allowances by the N emitting firms minus the exogenous supply of allowances noted Q_t and is characterised by a relation similar to Eq. (23) with t in place of T. By substituting for the net purchases of each firm their optimal expression according to Eq. (12), we obtain after some arrangements

$$p_t = \frac{\sum\limits_{i=1}^{N} \frac{\lambda_{it}+\mu_{it}z_t}{\gamma_i}}{\sum\limits_{i=1}^{N} \frac{1}{\gamma_i}} - \frac{Q_t}{\sum\limits_{i=1}^{N} \frac{1}{\gamma_i}} \quad \forall t < T \tag{25}$$

The market price p_t of the allowances at each date $t < T$ is therefore a weighted arithmetic mean of the implicit prices $\lambda_{it} + \mu_{it}z_t$ for the different firms, with the terms $\left(\frac{1}{\gamma_i}\right) / \left(\sum\limits_{i=1}^{N} \frac{1}{\gamma_i}\right)$ acting as weights. These weights only depend on the transaction cost parameters. The lower the transaction costs parameter (and therefore this cost itself) of a firm, the greater the weight of this firm in the market price of allowances. This average also undergoes a downward translation, the magnitude of which is proportional to the level of the exogenous supply Q_t of allowances.

In addition to the market clearing condition, on each date $t < T$ each firm i is subject to the dynamics of its banking described in Eq. (8). This relation takes the particular form (Eq. 21) for the end date T. Again, the focus is on the case where the implicit price of allowances is strictly positive for each firm at the end date T and thus:

$$0 = b_{iT} - u_{iT}^{\text{free}} + q_{iT} + x_{iT} + a_{iT} \tag{26}$$

By substituting for b_{iT} the right-hand term of Eq. (8) for $t = T - 1$ and by iterating so on until the initial level of banking b_{i0} appears, we obtain

$$0 = b_{i0} - \sum_{t=0}^{T} u_{iT}^{\text{free}} + \sum_{t=0}^{T} q_{iT} + \sum_{t=0}^{T} x_{it} + \sum_{t=0}^{T} a_{it} \tag{27}$$

Using the optimal abatement level and the optimal net purchase of allowances characterised respectively by Eqs. (11) and (12), and combining with Hotelling's rule (Eq. 17), the intertemporal banking constraint (Eq. 27) may finally be written as

$$\begin{aligned}\sum_{t=0}^{T} p_t = \gamma_i b_{i0} &+ \gamma_i \sum_{t=0}^{T} q_{iT} \\ &- \gamma_i \sum_{t=0}^{T} \frac{p_{yt}}{2p_{et}} \left(\sum_{m=1}^{M} \theta_m k_{mit} \right) \\ &+ \sum_{t=0}^{T} \lambda_{i0}(1+\rho_i)^t \\ &+ \sum_{t=0}^{T} \mu_{it} z_t \\ &+ \gamma_i \sum_{t=0}^{T} \frac{\lambda_{i0}(1+\rho_i)^t}{2p_{et}} \left(\sum_{m=1}^{M} {\theta_m}^2 k_{mit} \right) \\ &+ \gamma_i \sum_{t=0}^{T} \frac{\mu_{it} z_t}{2p_{et}} \left(\sum_{m=1}^{M} {\theta_m}^2 k_{mit} \right) \qquad \forall\ i \in \{1, \cdots, N\}\end{aligned} \tag{28a}$$

with

$$k_{mit} = k_{mi0}(1-\eta_m)^t + \sum_{s=0}^{t} I_{mis}(1-\eta_m)^{t-s} \tag{28b}$$

and I_{mis} is defined as in Eq. (19) whereas $\lambda_{it} = \lambda_{i0}(1 + \rho_i)^t$. For its part, once summed over all periods of existence of the permit market, Eq. (21) yields

$$\sum_{t=0}^{T} p_t = p_T + \frac{\sum_{t=0}^{T-1} \sum_{i=1}^{N} \frac{\lambda_{i0}(1+\rho_i)^t + \mu_{it} z_t}{\gamma_i}}{\sum_{i=1}^{N} \frac{1}{\gamma_i}} - \frac{\sum_{t=0}^{T-1} Q_t}{\sum_{i=1}^{N} \frac{1}{\gamma_i}} \tag{29}$$

where p_T is defined as in Eq. (24) except that the intertemporal banking constraint from $t = 0$ to $t = T - 1$ is used to write $b_{iT} = b_{i0} - \sum_{t=0}^{T-1} u_{iT}^{\text{free}} + \sum_{t=0}^{T-1} q_{iT} + \sum_{t=0}^{T-1} x_{it} + \sum_{t=0}^{T-1} a_{it}$ and substituted for b_{iT}. Again, the optimal abatement level and the optimal net purchase of allowances characterised respectively by Eqs. (11) and (12), combined with Hotelling's rule (Eq. 17), are used to finally express b_{iT} as a function of λ_{i0}.

The left hand sides of Eqs. (28a) and (29) being identical, we can also equalise their right hand sides. We thus obtain a system of N equations to be solved with respect to the N implicit prices λ_{i0} ($i \in \{0, \ldots, N\}$) of the different firms covered by the market. The case of the non-negative banking constraint has to be treated iteratively: in the first step, the solution for the λ_{i0} is found under the assumption that $\mu_{it} = 0 \; \forall \; i \; \forall \; t \in \{0, \ldots, T-1\}$; in the second step, the banking time path associated with this solution is computed and the compliance dates when at least one firm exhibits a negative banking are identified; in the same step, $\mu_{it} > 0$ associated with these dates and firms are determined so that the excess abatement and the excess purchase of allowances makes the non-negative banking constraint just satisfied; in the third step, the resulting new solution for the λ_{i0} ($i \in \{0, \ldots, N\}$) is found and the process is iterated until there is no new change in either the solution for the λ_{i0} ($i \in \{0, \ldots, N\}$) or the solution for the $\mu_{it} = 0 \; \forall \; i \; \forall \; t \in \{0, \ldots, T-1\}$. The resulting solution to this system of equations fully characterises the dynamic equilibrium of the market. These equations combine the principle of market clearing at each date with the intertemporal constraint governing the emissions of each firm. Equation (28a) shows that, in the absence of adjustment of the different types of capital (i.e. if $k_{mit} = k_{mi0} \; \forall \; i \; \forall \; t \in \{0, \ldots, T\}$), the system of equations to be solved is linear in the initial implicit prices. On the other hand, taking into account the adjustment of the different types of capital endogenously implies, according to Eqs. (28b) and (19) and noting that Hotelling's rule prevails (i.e. $\lambda_{it} = \lambda_{i0}(1 + \rho_i)^t$), that the system to be solved is quadratic in the initial implicit prices.

7 Data and Model Calibration

The remainder of this chapter proposes an analysis of the future of the EU-ETS using an approach that is more foresight than forecasting. With this aim in view, it is nonetheless required to calibrate the parameters of the theoretical model in the most realistic way possible. In addition, it was pointed out that baseline emissions and marginal abatement costs strongly depend on the price of the goods produced and on the carbon intensity of the production processes. These two characteristics are common to companies in the same sector but differ from one sector to another. They therefore imply that the sectoral scale is a fairly relevant scale for comparing the evolution of firms on an emissions allowance market like the EU-ETS. The calibration of the model therefore relied heavily on sectoral data. Data for each sector considered in the model are aggregated over all countries participating in the EU-ETS. The calibration uses the information available from the start of phase II of the EU-ETS up to 2017, the last year for which exhaustive information on all variables is available. Starting at phase II of the EU-ETS does not pose any problem as no emission allowances could be transferred from phase I, an experimental phase, to phase II. The banking of emission allowances can therefore be considered null in 2008. As most data available are provided on an annual basis, the unit of time used to calibrate the model is 1 year. Therefore, each date considered in the calibrated model is a compliance date.

The first series of data, covering years 1995–2017, was collected from the EU KLEMS database made available free of charge in its most recent version by the Vienna Institute for International Economic Studies.[2] These data relate to the total capital stock, expressed in millions of constant 2010 value, used in the different sectors with a breakdown according to the type of capital. As the model developed in the previous sections mainly refers to the capital directly involved in the production and pollution process, it is the category "other machinery and equipment" which was selected to approximate the total quantity of capital initially available (thus eliminating land, buildings, transport and telecommunication equipment). No information being available on the more or less polluting nature of this capital, the calibration adopted assumes that all the capital available in 2008 is "brown" capital. The calibration therefore considers the 2008 stock of "other machinery and equipment" as the benchmark for "brown" capital and assimilates any reduction in emissions per unit of capital to investment in "green" capital, thus limiting itself to two types of capital. Moreover, for the sake of simplicity, "green" capital is assumed to be perfectly carbon free so that its use generates no greenhouse gas emissions. In addition to quantities of capital, the EU KLEMS database also provides an index of capital price for "other machinery and equipment". The price of "green" capital has been set equal to that of "brown" capital and is approximated by the average of the national price indices weighted by the share of each country in the total level of capital "other machinery and equipment" over all European countries. Similarly, data on sectoral output levels, also expressed in millions of constant 2010 value, and corresponding index of prices are available in the EU KLEMS database. The choice of variable made as regards the output deserves some clarification. Indeed, in the model, it is the price of the output that appears. However, the idea is that this price can be used to capture variations in activity. In other words, the price is conceived as the result of a reduced form of equilibrium on the output market, and its variations are supposed to reflect mainly demand shocks, notably during the subprime crisis of 2008 and then during the Covid-19 crisis. However, the price index available in the database rather captures inflation on the value of the output than demand shocks. As a result, it is the output quantity indicator that has been used to trace the changes in what is designated as the price of the output in the model.

The second source of data is the EU Emission Trading System data set of the European Environmental Agency.[3] This data set provides information (expressed in tonnes of CO_2 equivalent) on surrendered allowances at the sector level for each year, the quantity of freely allocated allowances, and the total amount of allowances auctioned. Unfortunately, although both databases are based on the

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[2] https://euklems.eu/download/. See Stehrer et al. (2019).

[3] https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1.

NACE nomenclature, the sectoral breakdown used in the EU KLEMS database and that used in the EEA database are not the same. In order to cross-check the data from the two databases in a sufficiently consistent manner, the sectors have therefore been aggregated into six main sectors: “Combustion of fuels”, “Refining of mineral oil and production of coke”, “Metallurgy”, “Production of cement clinker and non-metallic mineral products”, “Production of pulp paper and cardboard”, “Production of chemicals”. The EEA database on emission trading covers the whole period of existence of the EU-ETS, from 2005 to 2019.

The last two sources of data are the Ember website for data on daily spot prices of allowances from 2008 onwards and the US Energy Information Administration website for data on daily crude oil price from 1987 onwards.[4] Average annual prices of allowances and crude oil have been computed from these two time series.

All the other parameters or variables of the model were either deduced from the data previously described or fixed in an ad hoc manner. The carbon intensity parameters characterising the “brown” production process for each sector has been set equal to the ratio (for year 2008) of surrendered emissions from the EEA database to the total sectoral output level in constant 2010 value computed from the EU KLEMS database for all countries participating in the EU-ETS. There is thus heterogeneity across sectors in terms of the benchmark carbon intensity. This is the main source of heterogeneity considered in the calibrated model, with the initial capital stock and the prices of capital and index of activity (i.e. quantity of output). By contrast, the transaction cost parameter, the depreciation rate of capital, the capital adjustment cost parameter (with one exception discussed *infra*), and the discount rate are assumed to be homogenous across sectors. This assumption mainly reflects the difficulties to fix their value on the basis of observables. The transaction cost parameter has been set so that a transaction of one tenth of the total amount of freely allocated allowances in 2008 costs 23% of their total market value. This percentage is actually outside the range of values obtained by Baudry et al. (2020) who find that, at the firm level, transaction costs per tonne of CO_2 ranges from 3% to 11% of the market price. The main rationale for fixing such a high transaction cost is that banking decisions reveal to be highly sensitive to its value, and the 23% assumption yields reasonable banking pathways.[5] The depreciation rate of capital has been set to 0.06. This means that about half of the stock installed at a given date has been depreciated 10 years later. The functional form chosen

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[4] https://ember-climate.org/data/carbon-price-viewer/. https://www.eia.gov/petroleum/data.php#prices.

[5] Lower values of the transaction cost parameter makes the non-negative banking constraint systematically binding for all sectors and most dates so that the main determinants of the price of allowances are no longer the sectoral Lagrange multipliers λ_{it} associated with the dynamics of banking but the KKT multipliers μ_{it} associated with the non-negativity constraint. It follows on that Hotelling’s rule becomes inoperative and the equilibrium is much more difficult to solve. Conversely, higher values of the transaction cost parameter imply high final levels of banking that are not sold out at the end of the market, contrary to the assumption made to solve the equilibrium on the basis of Eqs. (28a) and (28b).

for the adjustment cost function is simpler than the functional form used in the econometric literature (see for instance Hall, 2004). This simplified form helps solving the dynamic programming problem but complicates the calibration on the basis of existing empirical works. The parameter for the adjustment cost of capital has been set so that the stock of "green" capital is less than half the stock of "brown" capital in 2017, the starting year of the prospective analysis, for each sector.[6] The discount rate is 0.05 for all sectors. Finally, the productivity parameter A which appears in Eq. (3a) and which has been set to 1 in the theoretical model for notational convenience now has to be set at a value which is consistent with observed data. This parameter is systematically associated in a multiplicative form with the price p_{yt} of output and directly affects both the amount of output and the amount of emissions. In order to fix it, we first determine at each date from 2008 to 2017 what should be its value if the implicit price for each sector was just equal to the observed price of allowances and the resulting output level was just corresponding to the observed output level for the sector. The same computation is made with observed surrendered emissions. We are left with 20 different values of the productivity parameter per sector and calibrate its final value with the average value obtained for each sector.

Finally, as simulations start from 2018, we need assumptions about the banking level of each sector at this date. A solution could consist in simulating the banking decisions in period 2008–2017 and then use the computed banking levels in 2017 to initialise simulations from 2018 onwards. However, this solution encompasses important risks of error that could significantly affect simulations from 2018 onwards. The solution adopted was therefore rather to set a priori a level of banking reached in 2017 for each sector. More specifically, it is assumed that each sector has reached a banking level corresponding to its actual level of surrendered allowances, the reference year used for this calculation being 2017. This ad hoc assumption makes it possible to take into account the importance of banking during the price depression period ranging from 2010 to 2017 until backloading and then the MSR are adopted, without however generating a too high level of banking, making firms in the six sectors systematically reach the end of the market without being able to fully sold it out on the last date.

8 Simulation Results

The prospective analysis conducted in this section requires specifying a scenario for the time paths of permit allocations and permit auctions from 2017 onwards. The

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[6] For "Refining of mineral oil and production of coke", the adjustment cost parameter is set at a much higher value. Indeed, this sector highly differs from the others, starting with a very high level of emissions compared to the stock of capital in 2008 that induces large simulated investments in "green" capital from 2008 to 2017 in response to carbon pricing. This is clearly a drawback of assuming a homogenous capital adjustment cost.

proposed scenario is based on the European Commission roadmap for the EU-ETS.[7] The scenario thus provides for a gradual extinction of free allocations according to a linear decrease between 2018 and 2030. Beyond 2030, no free allocation is planned. Likewise, over the period 2018–2030, the scenario forecasts that auctions will decrease at an annual rate of 2.2%. Beyond 2030, i.e. after phase IV of the EU-ETS, the scenario is based on a linear extinction of auctions by 2050. In this way, the scenario is in line with the objective of carbon neutrality by 2050 as set by the European Union. In practice, the absence of allowances allocated free of charge or by auction after 2050 does not necessarily mean the end of the market. In fact, to comply with carbon neutrality, some companies that do not abate their emissions enough could seek to buy allowances held in banking by others, so that a secondary market in allowances could subsist for at least some time. The simulation work presented in this section overlooks this possibility and simplifies by considering that 2050 is also the end date of the EU-ETS.

The scenario on the dynamics of allocations and auctions is completed by two scenarios relating to the economic conditions surrounding the EU-ETS. It is these two scenarios that allow a prospective analysis of the consequences of the Covid-19 crisis. Each of these scenarios considers an exogenous, unanticipated and more or less transitory, shock on the economy. This shock results in an instantaneous variation of a given percentage of one or more exogenous variables of the model in 2020, followed by a gradual return to the value that prevailed in 2019. The resulting dynamics for the impacted variable v_t is

$$v_t = \begin{cases} v_{t-1} & \text{if } t < 2020 \\ (1-\alpha)\, v_{t-1} & \text{if } t = 2020 \\ v_{t-1} + \beta\,(v_{2019} - v_{t-1}) & \text{if } t > 2020 \end{cases} \tag{30}$$

The magnitude of the shock on v_t is captured by parameter α, whereas β measures the speed of reversion to the pre-shock situation. The first scenario considered thereafter builds on the observation that the Covid-19 has induced a drastic drop in both the level of activity, following a negative demand shock, and the price of fossil fuels as highlighted by Figs. 3 and 4a. However, recent observations suggest that the reversion to the pre-shock situation for the price of Brent is faster than that for the level of activity. Therefore, parameter α is set to 0.2 for the price p_{yt} of output in all sectors and 0.5 for the price of energy p_{et}, whereas parameter β is respectively set to 0.25 and 0.5. The shock is thus twice sharper for the price of fossil fuels, but reversion to the pre-Covid situation is also twice faster. The second scenario considers a similar shock for the price of outputs in the six sectors but no shock at all for the price of energy. It is intended to disentangle the effects of the shock on activity and the shock on the price of fossil fuels. Indeed, as already stressed when commenting on the level of emissions in Eqs. (5a) and (5b), the marginal abatement cost parameter in Eqs. (7a) and (7b), and the optimal

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[7] See https://ec.europa.eu/clima/policies/ets/revision_en.

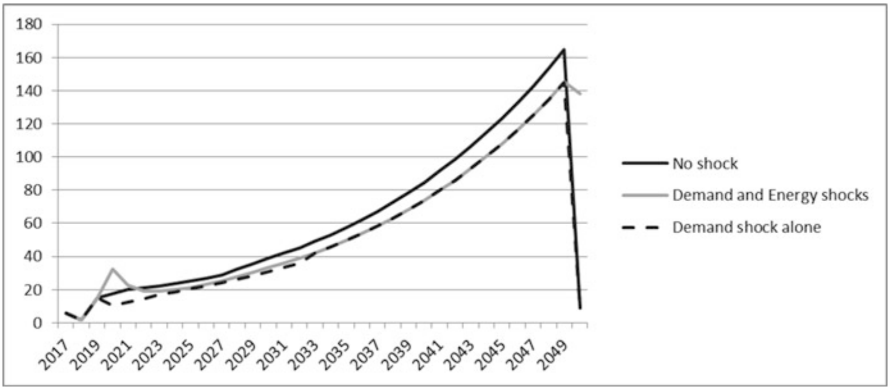

Fig. 5 Simulated time paths of the price of allowances (in euros per tonne) in the reference scenario and in the two alternative scenarios. (Source: simulations by the author)

investment rule (Eq. 19), the two types of shocks may have counteracting effects on the dynamics of the EU-ETS. Thereafter, the two scenarios are compared with a reference scenario where all prices remain at their 2019 level.

Simulation results on the time path of the price of allowances are illustrated by Fig. 5. It should first be noted that the slight decrease and then rise in the price between 2017 and 2019 are somewhat artificial. It results from the fact that the price in 2017 is that actually observed while that in 2018 is the price simulated with the model in the absence of a shock and under the assumptions detailed above as to the trajectory of allocations and auctions. The decrease between 2017 and 2018 is therefore of a purely technical nature. In the reference scenario, the price dynamics is clearly influenced by Hotelling's rule which governs the sectoral implicit prices of permits, excluding the constraint of non-negative banking. Total banking is relatively high over the entire period, so that on the final date, the sale of previously banked permits causes a sharp drop of the price. The demand shock taken alone reduces the price over the entire simulation period, except for the final date when the massive sales of banked permits lead to a, equilibrium price close to that of the reference scenario. Taking into account the shock on the price of fossil fuels in addition to the demand shock modifies the price trajectory at its very beginning and at its very end but seems neutral over the remainder of the simulation period. This additional shock initially reduces the marginal abatement cost, which is not completely offset by the increase in baseline emissions in accordance with Eqs. (5a), (5b) and (6). In the short term, this results in an increase in the price of permits that contrasts with the two other scenarios. At the end of the market lifespan, the price drop is much smaller than in the reference scenario.

Another important result of the model is the trajectory followed, at the aggregate level, by the capital stock in the baseline scenario. This stock tends to linearly decrease very slightly over the entire period studied, with an annual average rate of −0.79%. The first explanation for this result is structural: by considering a

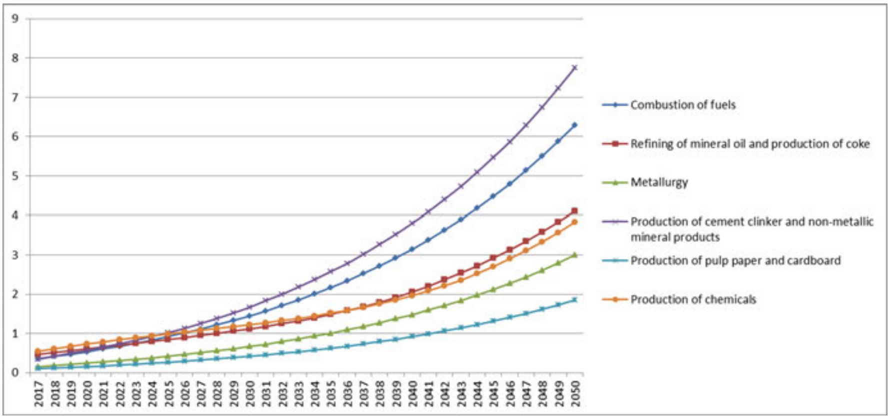

Fig. 6 Simulated time paths of the ratios between the stock of “green” capital and the stock of “brown” capital in the reference scenario for the six sectors. (Source: simulations by the author)

finite time horizon, the model introduces de facto a disincentive to invest as this horizon approaches. The second explanation lies in the definition of the reference scenario which is based on time invariant exogenous variables. There is therefore no exogenous factor likely to push investment upwards. The investments made are essentially replacement investments but not investments aimed at increasing production capacities.

One of the main originalities of the model is to include investment decisions and to take into account the heterogeneity of the firms covered by the EU-ETS. It is therefore worthwhile detailing the evolution of the capital stocks of the different sectors. This is what Figs. 6 and 7 do. Figure 6 shows the evolution of the ratio between “green” capital and “brown” capital in the reference scenario for the six sectors analysed. It clearly shows a strong change in the composition of capital by 2050. The “green” capital stock grows from around half of the “brown” capital stock to twice this stock in the worst case (sector “Production of pulp paper and cardboard”) and more than seven times this stock in the most favourable case (sector “Production of cement clinker and non-metallic mineral products”). It should be borne in mind, however, that these results are dependent on the value retained for the parameter of the adjustment cost of capital. Figure 7 complements Fig. 6 by showing the deviation of the ratio of “green” capital to “brown” capital in the case of the scenario with both the demand shock and the shock on the price of fossils fuels compared to the reference scenario. The result is contrasted, since the two joint shocks lead to the relative share of “green” capital increasing for certain sectors (“Production of cement clinker and non-metallic mineral products”) but decreasing for others (“Production of chemicals” and “Refining of mineral oil and production of coke”). For the other sectors, the impact remains low. The effect of the Covid-19 crisis in terms of capital restructuring can therefore be ambiguous.

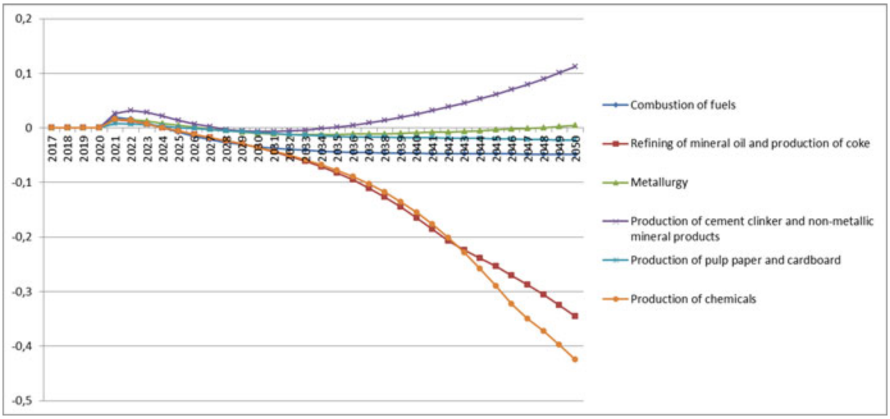

Fig. 7 Simulated time paths of the difference in the ratio between the stock of "green" capital and the stock of "brown" capital in the scenario with both a demand shock and a shock on the price of fossil fuels compared to the reference scenario. (Source: simulations by the author)

The last two figures aim at comparing the different scenarios in terms of the levels of capital at the aggregate level. Figure 8 reports the relative difference in the stocks of capital with, on the one hand, the scenario including both the demand shock and the shock on the price of fossil fuel and, on the other hand, the reference scenario. This difference is shown for the total stock of capital, the stock of "green" capital, and the stock of "brown" capital. Figure 8 highlights that, in the short term, the conjunction of the two shocks has a positive impact on the stock of "green" capital and a negative impact on the stock of "brown" capital. The net impact is positive which has been shown by the increase in the total stock of capital. However, the effects are reversed in the long term where the total stock of capital and the stock of "green" capital decrease compared to the reference scenario, whereas the stock of "brown" capital is increased. Figure 9 helps understand the contrast between short-term and long-term effects. In Fig. 9, the reported difference is that between the scenario with the demand shock only and the reference scenario. The absence of short-term increase in the total stock of capital and the stock of "green" capital in Fig. 9 indicates that the short term effects observed on Fig. 8 are attributable to the impact of the shock on the price of fossil fuels. This is consistent with the comments following Eq. (19) for the optimal investment rules when keeping in mind that the shock on the price of fossil fuels is assumed to be sharper but more transitory than the shock on demand. Even if the magnitude of the relative differences illustrated by Figs. 8 and 9 is small, these first simulation tests therefore suggest that the Covid-19 crisis is unlikely to accelerate the transition to a low-carbon economy. A more definitive conclusion, however, requires testing various variants of these scenarios in order to better appreciate the robustness of the results.

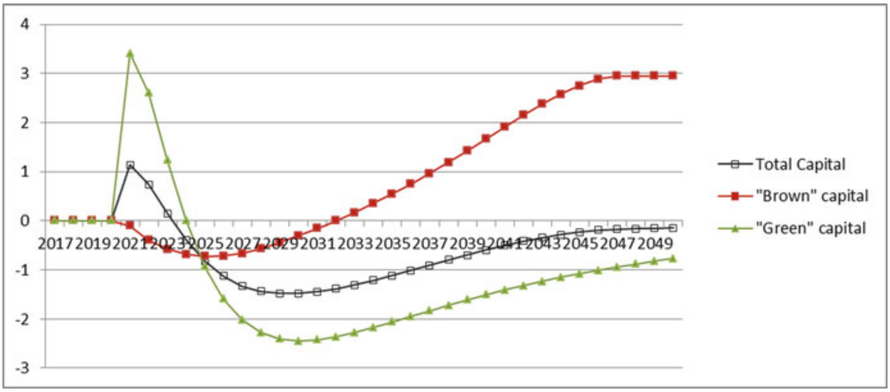

Fig. 8 Simulated time paths of the difference between the stock of capital with the scenario including both a demand shock and a shock on the price of fossil fuels and with the reference scenario, in % of the stock obtained with the reference scenario. (Source: simulations by the author)

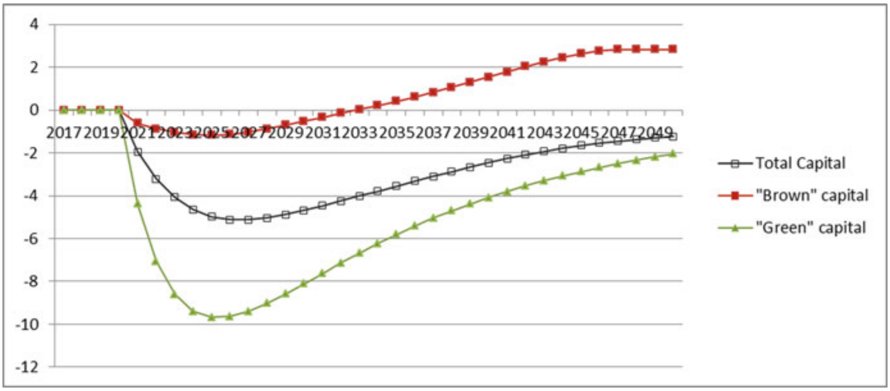

Fig. 9 Simulated time paths of the difference between the stock of capital with the scenario including a demand shock only and with the reference scenario, in % of the stock obtained with the reference scenario. (Source: simulations by the author)

9 Conclusion

In order to assess the potential effects over time of the Covid-19 crisis on the decarbonation trajectory of the economy, this chapter investigates the interactions between an emissions abatement strategy and a low-carbon investment strategy within the framework of an intertemporal emissions trading system. After having explained how investment decisions modify the abatement cost, and then modelled the market dynamically by taking this modification into account, the model developed has been calibrated using data relating to the EU-ETS. The first simulation results suggest a rather pessimistic conclusion. Indeed, only the negative shock on the price of fossil fuels is likely to induce a temporary acceleration of the transition to a low-carbon economy. The rise in the price of permits and the resulting "green" capital investment only appear in the short term and fades, or even reverses, rapidly in the medium and long term. In the long term, the more lasting effect of the negative demand shock dominates and slows down low-carbon investments.

These first results need to be substantiated. Their robustness must be confirmed, on the one hand by considering different variants of the scenarios and on the other hand by studying the sensitivity to calibration. In a more structural way, the introduction of a stochastic dynamics of the exogenous variables should make it possible to better represent the decisions of firms in the face of uncertainty surrounding the shocks associated with the Covid-19 crisis. This will be the subject of further research.

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Modelling Sustainability Transitions Under Covid-19

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JEL Classification C62, D91, Q56

1 Introduction

The recent Covid-19 pandemic poses new challenges to environmental economics in general and in particular to the transition to a sustainable economy. At first, national lockdowns aimed at fighting the pandemic have reduced polluting activities. However, any gain from this is going to be lost whenever economies manage to return to normal, and fail to produce any lasting effect. There is a second problem associated with the interlinkage between Covid-19 and human-induced environmental damage, which is the possible loss of attention or salience for environmental problems, and in general all effects from the pandemic that disadvantage green technologies and behaviours with respect to non-green ones.

Consumers' behaviour is a key factor of environmental degradation: it has been estimated that household emissions account for a share of 74% of total emissions in UK (Baiocchi et al., 2010). This factor is strongly influenced by the present pandemic, and cannot be overlooked by environmental policies. Sustainability transitions remain in the agenda of advanced economies, but the effects of the actual pandemic cannot be overlooked. In most cases, countries have indicated the explicit intention to align economic relief packages to environmental goals. It is crucial then to understand how Covid-19 impacts and policy actions linked to this impact will interact with people behaviours. With this objective, we develop

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a model of choice about technology adoption for a population of decision makers in a dynamic setting, in order to study the possible scenarios outcomes under a variety of conditions in terms of Covid-19 impacts, environmental damage intensity, and different behavioural hypothesis about how decision makers respond to the pandemic. Our main goal is to understand how Covid-19, environmental policies and behaviours interact within possible patterns of transitions to environmental sustainability.

The idea of technological and societal transitions dates back to Schumpeter (1942), while the 'complex' nature of transitions has been addressed later by the seminal work of Nelson and Winter (1982) and Arthur (1989). More recently, environmental degradation and climate change inspired the concept of 'sustainability transitions' (Kemp, 1994; Grin et al., 2010; Markard et al., 2012). However, the literature on modelling societal transitions and in particular sustainability transitions is rather new. A number of 'position' papers have reviewed and assessed different alternative modelling approaches as possible frameworks (Köhler et al., 2009; Safarzyńska et al., 2012; Zeppini et al., 2014). So far, actual attempt to modelling sustainability transitions has mainly used an agent-based approach, for instance Mercure et al. (2016) and Lamperti et al. (2020). In the present paper, we instead use a mathematical modelling framework, which provides analytical results, and resorts to numerical simulations with the tools of system dynamics and bifurcation theory (Medio & Gallo, 1995; Kuznetsov, 1998). This approach allows to meaningfully describe transitions as the non-linear effects of complex economic dynamics (Hommes, 2013).

We propose a model of choice between two substitute technologies, a non-polluting *green* technology and a polluting one, referred to as the *red* technology. Our working example is mobility choice, for example related to using a car or a bicycle. However, the model is general and can be applied to a variety of goods, services, means of production and also lifestyles. Agents in every period choose either one or the other. The discrete choice utility contains three main terms: an intrinsic profitability specific to a technology, allowing for subsidies to the *green* technology, a Pigouvian tax on the use of the *red* technology, with rebates for the *green* technology, and the environmental damage from the *red* technology. Covid affects utility in two ways. First, subsidies and tax are proportional to the Covid impact. The Covid impact reduces environmental damage. This opposition creates a trade-off that is crucial for understanding the impact of Covid on the transition to sustainable technologies. A differential impact of Covid for *green* and *red* technologies allows to describe reduced salience of environmental sustainability (Herrnstadt & Muehlegger, 2014) due to the pandemic. Utility terms are functions of the fraction of adopters of each technology, which in turn follows the logistic distribution of discrete choice theory. Consequently, the value of the fraction feeds back onto the decision environment. The model presents different regimes, from unique equilibrium to either multiple equilibria or periodic dynamics. For the different scenarios, we find conditions on tax and subsidies for avoiding a destabilising periodic dynamic and instead look for critical values of parameters fostering a transition to a self-sustaining equilibrium with a prevalence of *green choices*.

The theoretical framework of our model is the probabilistic setting of discrete choice, as introduced by McFadden (1981) and then extended to a dynamic choice setting by Brock and Hommes (1997). This framework has been applied to technology adoption by Zeppini (2015) and is extremely powerful in describing the dynamics of transition process by studying the collective decision system as a dynamical system. Here mechanisms such as bifurcations and equilibrium transitions become meaningful descriptions of the structural changes that characterise societal paradigm shifts and in particular sustainability transitions. The theoretical framework of our model allows using the techniques and concepts of system dynamics and stability analysis to describe and understand structural change in terms of the qualitative changes of a dynamical system. In particular, we can study a variety of different transitions patterns, from gradual changes to critical mass effects and social tipping points. Our model is also able to uncover dynamics different than stable equilibria, such as periodical patterns of behaviours where a portion of the population of decision makers change choice at every period.

The first part of the paper is an analytical study of the model, that provides a number of general theoretical results. We find conditions for the model having one or two stable equilibria and characterise the equilibria in terms of their parameters basin of attraction. This is extremely meaningful to understand what factors and parameters are responsible for the different equilibrium scenarios, and in particular how parameters set the critical levels behind social tipping points that can trigger a transition towards sustainable behaviours.

The second part of the paper uses numerical simulations techniques to study possible dynamic scenarios. In particular, bifurcation analysis provides detailed spectra of equilibrium outcomes for choice distributions across the population of decision makers. We consider two main dimensions of analysis: the space of Covid-19 impact and the policy space of the amount of subsidies for green technologies. The former has a natural positive approach: Higher levels of Covid-19 impact can result in a transition to larger shares of green technology if environmental policies linked to Covid-19 are in place. However, taxes with rebates are destabilising if there is relatively large environmental damage. Another finding is the behavioural tipping point induced by a critical level of Covid-19 impact, when this affects relatively more green choices. A more normative approach of model simulations studies the effect of different policy measures under different conditions of pandemic impact. Table 1 summarises the results of the numerical study in terms of the different outcomes from increasing subsidies in different conditions of policy mix, environmental damage intensity and Covid-19 impact.

The rest of the paper is organised as follows: Sect. 2 presents the theoretical model of discrete choice for sustainability transitions under Covid-19. Section 3 contains the simulation study of the model. Section 4 concludes with some policy messages and possible avenues for future research.

Table 1 Summary of possible outcomes induced by increasing subsidies for the green technology in different simulation scenarios for a strong policy mix with taxes and rebates (upper part) and for a mild policy mix (no taxes) with Covid-19 inducing limited attention to environmental damage for green choices

Strong policy mix	Low environmental damage	Large environmental damage
low Covid-19 impact	– gradual transition – tipping point	– gradual transition – no transition
Large Covid-19 impact	– gradual transition	– periodic dynamics – tipping point
Mild policy	Low environmental damage	Large environmental damage
Low Covid-19 impact	– gradual transition – no transition	– periodic dynamics – no transition
Large Covid-19 impact	– gradual transition	– periodic dynamics

2 A Discrete Choice Model of Transitions with Environmental Damage and Covid-19 Impact

2.1 The Modelling Framework

We build a discrete choice dynamic model of the decision between two technologies like in Zeppini (2015). Here the two technologies have a negative impact on the physical environment through pollution. One technology is 'green' in that its marginal environmental damage is lower than the 'red' technology. The two technologies are available for adoption by a large pool of decision maker. The discrete choice utility of an agent i for the technology adoption decision reads as follows:

$$W_i = \begin{cases} W_g = \lambda_g + s(v) + rt(v)(1-x) - \delta_g(v)(1-x) \\ W_r = \lambda_r - t(v) - \delta_r(v)(1-x). \end{cases} \tag{1}$$

Here λ_g and λ_r are intrinsic profitability levels for the two technologies. The term $s(v) = s_0(1 + av)$ is a subsidy for the *green* technology, which is increasing in the impact of Covid v if $a > 0$, while if $a = 0$ the subsidy is independent of Covid, and equal to $s_0 > 0$. The term $t(v) = t_0(1 + bv)$ is an environmental tax on the *red* technology, which is in turn increasing with the impact of Covid v if $b > 0$, decreasing if $b < 0$ and independent of it if $b = 0$, in this case having a rate $t_0 > 0$. Taxes can have rebates to the *green* technology if $r > 0$. With x indicating the share of the population that has adopted the *green* technology, rebates are proportional to $1 - x$, i.e. the share of *red* technology choices. Finally, environmental damage is proportional again to the share of *red* technology choices, because only this one is polluting, while the green technology is 'clean'. Environmental damage utility terms are $\delta_g(v)(1-x)$ for an adopter of the *green* technology and $\delta_r(v)(1-x)$ for an adopter of the *red* technology. Marginal damage factors are

$$\delta_g(v) = \alpha \frac{\delta}{1+k_g v}, \quad \delta_r(v) = \frac{\delta}{1+k_r v}, \tag{2}$$

with $\alpha > 0$, $k_g, k_r > 0$ and v the impact of Covid. If $\alpha = 1$ and $k_g = k_r$, environmental damage on adopters of *green* and *red* technologies is the same. If $\alpha < 1$ with $k_g = k_r$ there is relatively less impact on *green* adopters, and the other way around if $\alpha > 1$. As for parameters k_g and k_r, they allow to describe a behavioural effect, namely a lower perceived environmental damage for one or the other choice option, due to a different impact of Covid on the intrinsic motivation for a *green* choice, or a more limited attention of the *red* technology adopters for environmental damage.

The difference in utility levels of the two technologies is the following:

$$\Delta W(x) = W_r - W_g = \lambda - s(v) - t(v)(2-x) - \delta(1-x)\left[\frac{1}{1+k_r v} - \frac{\alpha}{1+k_g v}\right]. \tag{3}$$

There is a critical value of the share of *green* choices $\tilde{x}$ that makes agents indifferent between the two technologies, with $\Delta W(\tilde{x}) = 0$. This condition can be written as follows:

$$rt(v)(1-x) + \delta D(v)(1-x) = \lambda - s(v) - t(v). \tag{4}$$

where $D(v) = \frac{1}{1+k_r v} - \frac{\alpha}{1+k_g v}$. The solution of this equation is the indifference level of green choices fraction:

$$\tilde{x} = 1 - \frac{\lambda - s(v) - t(v)}{rt(v) + \delta D(v)}. \tag{5}$$

Following here we list a number of results that provide information about the indifference level of choices' distribution in the population.

Result 1 The larger the profitability gap λ, the smaller $\tilde{x}$. If $\tilde{x} \in [0, 1]$ and $|f'(x)| < 1$, the indifference level is a proxy of equilibrium for the fraction x. In this scenario, a larger λ means that few agents choose the green option.

The dependence on taxes and subsidies before Covid-19 (or Covid-19 free) is as follows (set $a = b = 0$, so only consider δ_0 and t_0):

Result 2 The indifference level $\tilde{x}$

- Increases with subsidies if $D(v) > 0$
- Decreases with subsidies if $D(v) < 0$

where $D(v)$ is the difference in environmental damage between green and red choices.

Result 3 Without environmental damage perception ($D(v) = 0$) and without subsidies, $\tilde{x}$ increases with taxes, as $\tilde{x} = \frac{1}{r} - \frac{\lambda}{rt(v)}$.

The following results describe the effect of taxes rebate rate r on the indifference level $\tilde{x}$.

Result 4 The higher the rate r of rebates, the lower $\tilde{x}$ is; this is because rebates are linked to red choices and increase with their fraction $1 - x$.

We see this effect more generally within the trade-off of taxes when subsidies and/or perceived environmental damage are present.

Result 5 If environmental damage would not be perceived, $\tilde{x}$ increases with taxes if $s < \lambda$, but $\tilde{x}$ decreases with taxes if $s < \lambda$ (where $\tilde{x} = \frac{1}{r}(1 + \frac{s-\lambda}{t}) = \frac{s+t-\lambda}{rt} = \frac{1}{r} + \frac{s}{rt} - \frac{\lambda}{rt} = \frac{1}{r}(1 + \frac{s}{t}) - \frac{\lambda}{t} = \frac{1}{r}(1 + \frac{s-\lambda}{t})$).

Because of the rebate, taxes and subsidies are substitutes. However, there is a critical level such that if subsidies are too large, the effect of taxes is detrimental. The effect of taxes in the general case when perceived environmental damage is presented is more complicated. In order to study the effect of the tax rate t on the indifference fraction level, we proceed as follows. We set the condition for this effect to be positive:

$$\frac{d\tilde{x}}{dt} = \frac{rt + \delta D - r(s + t + \lambda)}{(rt + \delta D)^2} > 0.$$

$$\Rightarrow rt + \delta D - rs - rt + r\lambda > 0.$$

$$\Rightarrow \delta D + r\lambda > rs.$$

$$\Rightarrow s > \frac{\delta D}{r} + \lambda. \tag{6}$$

We express this condition in terms of the following result:

Result 6 As long as subsidies s remain below a certain level ($\frac{\delta D}{r} + \lambda$), the indifference value of green choices increases with the tax rate. But above this level, the fraction of green choices that makes agents indifferent decreases with the tax rate.

This last result has strong implications for policy: Depending on the level of subsidies in place, adding taxes can have extremely different effects on the distribution of choices.

This analysis paves the way for the study of the effect of Covid-19 impact on the indifference point of green and red choices. By making this effect explicit, (5) becomes

$$\tilde{x}(v) = \frac{s_0(1 + av) + t_0(1 + bv) - \lambda}{rt_0(1 + bv) + \delta(\frac{1}{1+k_r v} - \frac{\alpha}{1+k_g v})}. \tag{7}$$

Result 7 Without perceived environmental damage ($\delta = 0$), and with $r < 1$, $\tilde{x}$ increases with the impact of Covid-19 v whenever $a > b$ if $\lambda > 0$, and in general. This result descends from a policy mix with a stringency that is proportional to the impact of Covid-19. If such impact is transferred to subsidies relatively more than taxes ($a > b$), the effect of the latter is relatively stronger, and the indifference level of green choices increases with the Covid-19 impact. If instead the impact of Covid-19 is transferred more onto taxes than subsidies ($a < b$), then the trade-off mechanism of rebates becomes prevalent, and the indifference level of the fraction of choices decreases with the impact of Covid-19.

The full mechanism with perceived environmental damage is more complicated. In particular, if Covid-19 affects green and red choices differently, it makes perceived environmental damage a non-monotonic factor:

$$D(v) = \frac{1}{1 + krv} - \frac{\alpha}{1 + kgv}. \tag{8}$$

A numerical example is $D(v) = \frac{1}{1+v} - \frac{\alpha}{1+2v}$.

2.2 *Decision Feedback*

Discrete choice theory is founded on the concept of *random utility*. In such framework, the utility (1) is the deterministic component of the 'true' utility experienced by an individual. The random component is a iid noise $\epsilon(i)$ which is known only to the individual i. The full random utility enjoyed by individual i is then $\tilde{W}_i = W + \epsilon(i)$. The noise terms have a double interpretation: It can express heterogeneous preferences (McFadden, 1981) or bounded rationality (Brock and Hommes, 1997). In both cases, a common assumption in discrete choice theory is that noise terms are independent and *extreme value* distributed across individuals. Accordingly, the probability of each choice option is distributed as a logit function. In particular, the probability of a green choice here is

$$Prob(green) = \frac{e^{\beta W_g}}{e^{\beta W_g} + e^{\beta W_r}} = \frac{1}{1 + e^{\beta \Delta W}}. \tag{9}$$

The parameter $\beta \in [0, \infty)$ is called *intensity of choice*, and is inversely related to the variance of the variability of random utility across agents. Within the interpretation of preferences shocks, a larger β means that decision makers are more similar to each other. Adopting the bounded rationality interpretation instead, a larger β means that agents are more capable of adopting the best choice option.

A population approach to the discrete choice of individuals allows to see the choice probability as the fraction of agents who choose one of the two alternative options. Since utility levels depend on the same fraction, this results in an endogenous mechanism for the determination of behaviours. Let us rewrite the difference of utility levels (3) between the green and the red technologies:

$$\Delta W(x, v) = \lambda - s(v) - t(v) - [rt(v) + \delta D(v)](1-x) = L(v) - k(v)(1-x), \tag{10}$$

with $L(v) = \lambda - s(v) - t(v)$ and $k(v) = rt(v) + \delta D(v)$. According to (9), the probability distribution of the discrete choice utility is

$$f(x) = \frac{e^{\beta W_g(x)}}{e^{\beta W_g(x)} + e^{\beta W_r(x)}} = \frac{1}{1 + exp[\beta \Delta W(x, v)]}. \tag{11}$$

In a large population, this probability is equal to the actual fraction of choices, so that the discrete choice here is a self-consistent decision mechanism. And the equilibria are set endogenously by fixed points x^* such that $x^* = f(x^*)$.

The probability distribution function f sets the feedback mechanism of choices, with either positive feedback or negative feedback. For the probability $f(x)$ to be increasing (positive feedback), $f'(x) > 0$, we need to have

$$f'(x) = -[f(x)]^2 \beta \Delta W'(x) e > 0 \Leftrightarrow \Delta W'(x) < 0. \tag{12}$$

The condition for positive feedback is the following, then

$$\Delta W'(x) = K(v) = rt(v) + \delta D(v) = rt_0(1 + bv) + \delta \left(\frac{1}{1 + krv} - \frac{\alpha}{1 + kgr} \right) < 0. \tag{13}$$

Result 8 The direction of the decision feedback (positive or negative) depends on tax rebates and the differential perceived environmental damage among green and red choices.

This condition can be rewritten as

$$\delta \frac{\alpha(1 + k_r v) - (1 + k_g v)}{(1 + k_r v)(1 + k_g v)} > rt_0(1 + bv). \tag{14}$$

Result 9 If $1 + k_g v > \alpha(1 + k_r v)$, there cannot be a positive feedback. This is a sufficient condition for a negative feedback, which can also be written as $D(v) > 0$ or

$$\frac{1}{1 + k_r v} > \frac{\alpha}{1 + k_g v}. \tag{15}$$

Result 10 If the impact of Covid-19 is such that perceived (the salience of) environmental damage $v(1 - x)$ from the red choice option becomes smaller for the green option than for the red one, then we have a negative decision feedback.

A common assumption is that perceived damage is larger for the green choice option, $\alpha\delta(1 - x) > \delta(1 - x)$ with $\alpha > 1$. The impact of Covid-19 may reverse this as long as it is stronger or perceived damage with a green choice than within a red choice with $D(v).0$, $1 = k_g v > \alpha(1 + k_r v)$ and $v > \frac{\alpha-1}{k_g-\alpha k_r}$ (critical Covid-19 impact to have negative feedback).

In the case of equal perceived damage before Covid-19 ($\alpha = 1$), the impact of Covid-19 makes perceived damage of green choice more salient as soon as $k_g > K_r$. Put differently, if Covid-19 lowers perceived damage more for green choices, then we always have a negative feedback. Without tax rebates ($r = 0$) the condition $D(v) > 0$ is necessary and sufficient for negative feedback, while the opposite condition, $v < \frac{\alpha-1}{k_g-\alpha k_r}$, gives positive feedback. This means the following in terms of Covid-19 impact:

Proposition 2.1 *Without tax rebate, there is a critical v_α threshold of Covid impact v such that:*

- *For $v > v_\alpha$, we have negative feedback,*
- *For $v < v_\alpha$, we have positive feedback.*

If $\alpha > 1$ we have $v_{\alpha=1}$, and there is no threshold incoming that decision feedback is negative whenever $k_g > k_r$, i.e. when Covid-19 impact is stronger on green choices' environmental damage salience.

The general case for the direction of feedback with tax rebates expressed by (13) can be studied by looking for a numerical solution of inequality (14). However, even without a closed form solution, we can derive the following results:

- When impact of Covid-19 is low ($v \to 0$) the difference salience of environmental damage for green and red choices, stronger for the former ($\alpha > 1$) induces positive feedback.
- To this rebates oppose a negative feedback element.
- Covid-19 can depress the salience of environmental damage relatively more for the green, and this can lead to a shift from positive to negative feedback.
- Negative feedback is destabilising and can lead to overshooting of choices.
- With rebates, the critical value of Covid-19 impacts above which we have relatively low negative feedback.
- Without rebates, there is a higher threshold of Covid impact above which we obtain negative feedback.

2.3 Stability Analysis of the Model

We model choice with using the probability distribution $f(x)$ as an evolutionary revision protocol (Zeppini, 2015):

$$x_t = f(x_{t-1})$$

This amounts to assuming myopic behaviour of agents regarding the fraction of choices for green and red options. Within this dynamical setting, an equilibrium is a fixed point $x^* = f(x^*)$.

Proposition 2.2 *Since $\Delta W(x)$ is linear in x, the probability distribution $f(x)$ is s-shaped and monotonic. This implies the following:*

- *There are at most two stable equilibria,*
- *There always exist at least one equilibrium (although this can be unstable),*
- *The possible dynamics scenario are either convergence to one equilibrium or periodic dynamics with period 2 cycles.*

A stable equilibrium is a fixed point x^* for which

$$|f'(x) < 1|.$$

We can then derive a number of necessary or sufficient conditions for unicity or multiplicity of equilibria, as well as for periodic dynamics.

Proposition 2.3 *A sufficient condition for unique equilibrium is*

$$\frac{1}{4}\beta[rt_0(1+bv)] + \delta[\frac{1}{1+krv} - \frac{\alpha}{1+kgr}] < 1. \tag{16}$$

Proof

$$f'(x) = \beta \Delta W'(x)\frac{1}{4}[\text{sech}(\frac{\beta}{2}\Delta W(x))]^2.$$

Since *sech*: $\mathbb{R} \rightarrow (0, 1]$, then $\frac{\beta}{4}|\Delta W'(x)| < 1 \Rightarrow |f'(x) < 1|$, then $\frac{1}{4}\ \beta|k(v)| < 1$. □

The effect of Covid-19 through tax rebates is destabilising, because it contributes to an increasing $f'(x)$. Since we know that tax rebates proportional to the fraction $1 - x$ of red choices give a negative feedback, if the system loses stability due to tax rebates the dynamic outcome is periodic dynamics. This is due to overshooting of choices: If many agents opt for the red options, there are large tax revenues redirected to the green option which becomes then more attractive. As a result, many agents adopt the green option, with effect of reducing the tax income and the rebate. But then the red option becomes more attractive again and the story repeats.

The effect of Covid-19 through reduced salience of environmental damage is a stabilising force as long as $k_r \approx k_g$, i.e. as long as its marginal effect on perceived damage is comparable among green and red choices. However, there is a scenario where the effect of Covid-19 through perceived environmental damage is destabilising. Let us consider a large physical marginal damage δ, and $\alpha \approx 1$ (i.e. comparable perceived damage before Covid-19). In this scenario, perceived damage in red and green choices almost offset each other when comparing the two. But if the marginal impact of Covid-19 on perceived damage is very different between the two choice options, with $k_g \gg k_r$ or $k_g \ll k_r$, then $|f'(x)|$ increases with Covid-19 impact v. For instance, let us assume that $\alpha = 1$, $k_r = 0$ and $k_g = 1$. The difference in perceived damage is

$$\delta |1 - \frac{1}{1 + kgv}|.$$

Initially this is zero, and then it increases up to δ with v increasing.

Proposition 2.4 *Depending on the regime of positive or negative decision feedback, a necessary condition for multiple equilibria or periodic dynamics is*

$$\frac{1}{4}\beta \left[rt_0(1 + bv) + \delta \left| \frac{1}{1 + k_r v} - \frac{\alpha}{1 + kgv} \right| \right] > 1. \tag{17}$$

This is the sufficient condition (16) reversed. Actually we see that whenever we have positive feedback with $f'(x) > 0$, condition (17) is necessary for multiple equilibria. On the contrary, when we have negative feedback, condition (16) is sufficient to have convergence (with up and down dynamics) to a stable equilibrium, while condition (17) is necessary for a periodic dynamic outcome with orbits of period-2.

There is another necessary condition for multiple equilibria in a regime of positive feedback, which corresponds to a sufficient condition for a unique equilibrium.

Proposition 2.5 *With positive feedback, sufficient conditions for unique equilibrium are*

$$\frac{\lambda - s(v) - t(v)}{rt(v) + \delta D(v)} < 0 \tag{18}$$

and

$$\lambda - s(v) - t(v) > rt(v) + \delta D(v). \tag{19}$$

Proof The conditions above imply that $\tilde{x} < 0$ and $\tilde{x} > 1$, respectively. As long as β is finite, there can only be one fixed point in [0, 1]. □

Corollary 2.1 *The opposite of conditions (18, 19) are necessary for multiple equilibria.*

3 Simulation Study of Sustainability Transitions Under Covid-19

3.1 Simulations Setting

We perform a large variety of simulation runs of the model to explore the equilibrium outcome in the long run under different conditions. The main variable of interest is the share of green choices, and how its equilibrium (long run) value depends on the different parameters of the model. In particular, we focus on the transition dynamic towards a sustainable outcome conceived as a majority of green choice. In this light, we perform simulations that explore the impact and the possible transition outcome induced by changes in two main factors: a policy channel such as the size of subsidies for the green technology, and the impact of Covid-19. These two factors represent the point of view of our analysis, in order to look at sustainability transitions under Covid-19 from two different angles.

Our numerical tool of analysis is the so-called bifurcation diagram: This is a graph representing the long run value of the state variable of the model (the share of green choices in our cases) for many different values of one parameter. The parameter is finely tuned, and for each value the model is simulated starting from several different initial conditions and the long run value of the state variable recorded. If only one value is recorded in the long run, it is an equilibrium value. If two values are recorded for a single parameter values, this means that we have a period-2 orbit and periodic dynamics. Overall, the bifurcation diagram seemingly provides a graph of the long run values of the state variable as a function of the parameter under study.

Following here we present and analyse different simulations of the model in different parameters settings. The main dimensions under study are the Covid-19 impact, represented by the parameter v and the subsidies intensity, represented by the parameter s_0. Other parameters are the subject of analysis for setting different conditions in order to study transitions in different scenarios. These are the parameter δ, α, t_0 and the couple k_r, k_g:

- δ measures marginal damage of both technologies' adoption choices;
- α represents how much more (if positive) or less (if negative) the green technology adopters 'suffer' from the pollution of the red technology adopters (to the extent that environmental damage is 'perceived' environmental damage, the parameter $\alpha > 0$ measures how much environmental damage is more salient for green technology adopters);
- t_0 is the stringency of environmental policy when this is implemented through a tax on the use of the red technologies, such as a Carbon tax;
- k_g and k_r are the coefficient measuring the marginal impact of Covid-19 on environmental damage: If $k_g > k_r$ the impact of Covid makes environmental damage for green adopters lower (this can be understood as lower physical impact

due to restriction on the use of technologies, or lower perceived damage, due to diminished attention to environmental damage by green adopters).

The rest of the parameters are not the subject of the simulation study, and their value is set as follows: $\beta = 4$ (rationality parameters), $\lambda_g = 1$, $\lambda_r = 2$ (the red technology is twice as profitable than the green technology), $a = b = 1$ (increasing rate of Covid-19 induced subsidies and taxes, respectively).

3.2 Exploration of Covid-19 Impact on Sustainability Transitions Under Different Policies

In a first series of simulation studies, we consider increasing level of Covid-19 impact, and look at how the long run value of green choices changes accordingly. We initially consider an environmental policy mix consisting prevalently of taxes on the red technology with rebates to the green technology, and a very small level of subsidies. Three different scenarios are considered, with three different degrees of environmental damage (Fig. 1). Covid-19 induces a move towards sustainability, with doubling the shares of green choices in equilibrium from 40% to 80%. Interestingly, in a scenario of more serious environmental damage such a transition experiences a range of periodic dynamics (the two branches of the bifurcation diagram in the central and the right panel of Fig. 1). The reason for periodic dynamics is the rebates mechanism, which creates a minority game effect: more red choices mean larger taxes revenues transferred to the green technology, which makes this one relatively more attractive. As a result though, green choices shares increase, and red choices decrease, which in turn reduces tax revenues and make the green choice less attractive. A larger environmental damage amplifies this minority game mechanism. We may conclude that a policy mix with tax rebates can transform the effect of Covid-19 into a transition to sustainability, but if environmental damage from the taxed polluting technology is too large, the rebates mechanism brings an undesirable instability of choices.

We now consider a different policy mix: a higher level of subsidies s_0, and no rebates associated with taxes ($r = 0$). In particular, we study the effect of a larger environmental damage for green choices as measured by the parameter α (Fig. 2). A higher level of subsidies favours a multiple equilibria outcome, together with differential environmental damage. An increasing impact of Covid makes the choice system switch from an equilibrium with little or no green adoptions to the alternative desirable equilibrium where green choices are prevalent. A multiple equilibrium scenario poses a serious challenge for policy: In such a context, when policy increases the level of subsidies, almost nothing happens in terms of behaviours distribution. We need to reach the ‘tipping point’ represented by the unstable equilibrium where the population tips from the undesirable lock-in into the equilibrium with almost no green choices to the equilibrium with a prevalence of green choices (Fig. 2, centre and right panels). This means that an environmental

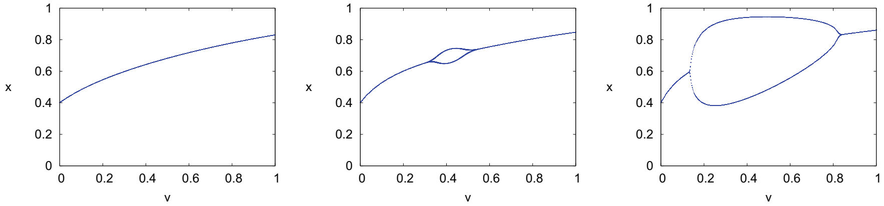

Fig. 1 Equilibrium value of the share of the green choices as a function of Covid-19 impact v. The role of absolute environmental damage. *Left*: $\delta = 1$ (low environmental damage). *Centre*: $\delta = 3$ (moderate environmental damage). *Right*: $\delta = 5$ (high environmental damage). Here $t_0 = 0.5$, $r = 1$ (taxes and rebates), $s_0 = 0.1$ (subsidies), $\alpha = 1$ (same environmental damage on green and red choices' utility), $\beta = 4$, $\lambda_g = 1$, $\lambda_r = 2$, $a = b = 1$ and $x_0 = 0.5$

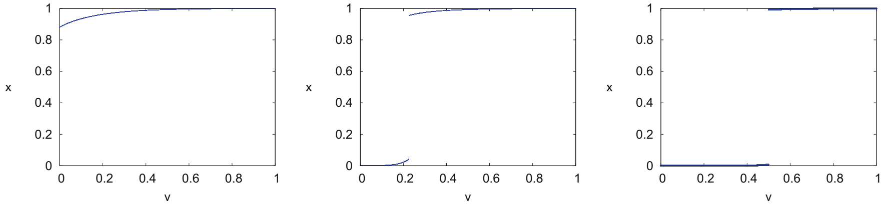

Fig. 2 Equilibrium value of the share of the green choices as a function of Covid-19 impact v. The role of differential environmental damage with larger subsidies $s_0 = 1$. *Left*: $\alpha = 1$ (equal damage on green and red choices). *Centre*: $\alpha = 2$ (twice as large damage on green choices). *Right*: $\alpha = 3$ (thrice as large damage on green choices). Here $\delta = 1$, $t_0 = 0.5$, $r = 0$ (taxes without rebates), $\beta = 4$, $\lambda_g = 1$, $\lambda_r = 2$, $a = b = 1$ and $x_0 = 0.5$

policy may find it difficult to justify its effort initially, as no substantial outcomes can be obtained. It is then important to raise awareness on the highly non-linear effect of policy in such multiple equilibria environment, where once the critical level is reached society can 'tip' to the desirable equilibrium of self-sustaining green choices, and exploit such a virtuous behavioural lock-in. Finally, we notice that when environmental damage is more serious (larger δ) the tipping point to the desirable equilibrium occurs at a higher level of Covid-19 impact.

The occurrence of periodic dynamics is not only an outcome of taxes with rebates. A similar minority game mechanism can be triggered by the different environmental damage of red adoptions on the utility of the two choices. As pointed out above, a different damage can occur because of differences in the physical environment that characterises each choice (e.g. choosing to drive a car or a bicycle) or because environmental damage is perceived differently by a decision maker depending on which choices she makes. It turns out that when Covid-19 impacts differently the marginal environmental damage for green and for red adoptions, a minority game mechanism arises, with negative feedback of choices: When the number of green adoptions increases, a green choice becomes less attractive, because damage on green adoptions becomes larger than damage on red adoptions. The reason is that environmental damage is caused by red adoptions, but in such

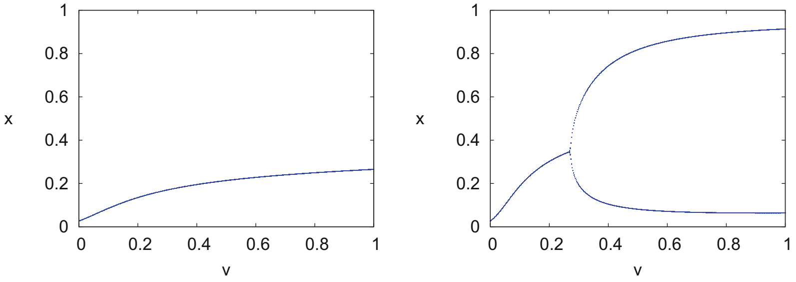

Fig. 3 Equilibrium value of the share of the green choices as a function of Covid-19 impact v. The case where Covid-19 impact is much stronger on green adoptions, with $k_g = 5$ and $k_r = 0.1$, without taxes $t_0 = 0$ and low subsidies $s_0 = 0.1$. *Left*: $\delta = 1$. *Right*: $\delta = 2$. Here $\alpha = 1$, $\beta = 4$, $\lambda_g = 1$, $\lambda_r = 2$, $a = b = 1$ and $x_0 = 0.5$

scenario Covid impact depresses relatively more the utility of green choices. Within the interpretation of perceived environmental damage, this amounts to diminished attention cause by Covid-19.

In order to study specifically the negative feedback scenario induced by Covid-19 through environmental damage, we 'switch off' the tax policy channel ($t_0 = 0$), and keep a low level of subsidies with $s_0 = 0.1$. At the same time, marginal environmental damage decreases at rate $k_g = 5$ for green adoptions, and only at rate $k_r = 0.1$ for red adoptions (see Eq. 2). We consider two levels of marginal damage before Covid-19, with $\delta = 1$ and $\delta = 2$. The simulations results are reported in Fig. 3. When marginal damage before Covid-19 is relatively low, Covid-19 induces a moderate change towards higher shares of green adoptions (left panel of Fig. 3). If damage δ is relatively larger, there is a critical level of Covid-19 impact (bifurcation value) above which the choice system loses stability, and converges to a periodic orbit of period 2 (right panel of Fig. 3). Above this critical level, a number of decision makers switch behaviour every period from a green to a red adoption, and this number increases with Covid-19 impact. Figure 4 shows two examples of time series for the first 50 periods, one with diminishing oscillations and convergence to a stable equilibrium ($v = 0.2$, left panel), and one with oscillations of increasing amplitude converging to a stable periodic orbit ($v = 0.4$, right panel).

The negative feedback of this scenario is caused by another minority game mechanism, similar to the one of taxes with rebates. Here it is Covid-19 impacting largely more green adoptions, either physically, or through lower perceived damage. The latter interpretation is particularly compelling for environmental policy designed under the pandemic. Covid-19 impact lowers overall the use of polluting technologies. However, this positive effect on the environment can be undermined by a diminished attention for the environment if this hits relatively more green adopters.

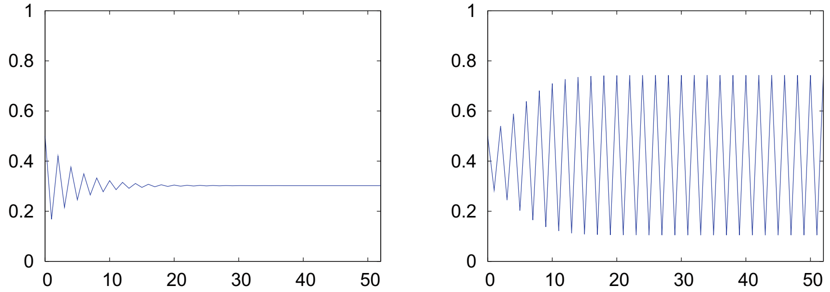

Fig. 4 Time series of the share of the green choices as a function of Covid-19 impact v. The case where Covid-19 impact is much stronger on green adoptions, with $k_g = 5$ and $k_r = 0.1$, without taxes $t_0 = 0$ and low subsidies $s_0 = 0.1$. Scenario with relatively large environmental damage before Covid-19, with $\delta = 2$. *Left*: $v = 0.2$. *Right*: $v = 0.4$. Here $\alpha = 1$, $\beta = 4$, $\lambda_g = 1$, $\lambda_r = 2$, $a = b = 1$ and $x_0 = 0.5$

3.3 Exploration of Subsidies Effect on Sustainability Transitions Under Different Levels of Covid-19 Impact

We now take a different and complementary angle in our simulation study, and explore directly the effect of policy intervention on the discrete choice distribution in equilibrium. We study first a strong policy mix where subsidies are accompanied by taxes with rebates, and consider a high and a low Covid-19 impact on the economy. The simulations of Fig. 5 are obtained for an impact $v = 0.1$, and refer to different combinations of environmental marginal damage δ before Covid-19 and the differential damage parameter α between green and red adoptions. When environmental damage before Covid-19 impacts on green and red adoption equally ($\alpha = 1$), an increasing amount of subsidies s_0 leads to a smooth increase in shares of green choices, with almost no difference for small or large environmental damage δ (top panels). This outcome contrasts sharply with the case of different impact of environmental damage on green and red adoptions (bottom panels). In this case the response of the fraction of choices in equilibrium responds in a markedly non-linear fashion to increases of the level of subsidies, with a pronounced s-shape pattern (bottom-left panel). If environmental damage is relatively strong, the same levels of subsidies do not manage to induce any increase in green shares (bottom-right panels). In such conditions, an environmental policy may get frustrated by not observing any appreciable result in terms of moves towards sustainable (green) choices, until a critical mass level of subsidies is reached. At this point, the marginal return on terms of green shares is huge, but stronger environmental damage may place such critical mass subsidies at un-reachable levels.

The case of relatively larger Covid-19 impact $v = 1$ (ten times larger) is presented in Fig. 6. Here the case of small environmental damage is fairly similar across situations of equal and different damage on green and red choices (left panels): A policy mix proportional to Covid-19 impact delivers larger shares of

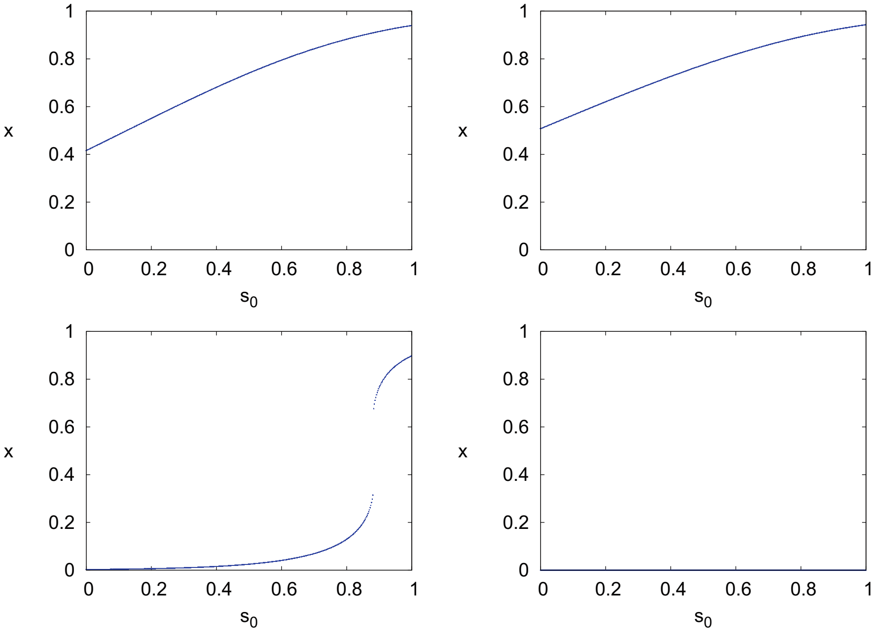

Fig. 5 Equilibrium value of the share of the green choices as a function of subsidies s_0. Strong policy mix with taxes and rebates $t_0 = 0.5$, $r = 1$. Scenario with relatively small Covid-19 impact, $v = 0.1$. *Top-left*: $\alpha = 1$, $\delta = 1$. *Top-right*: $\alpha = 1$, $\delta = 5$. *Bottom-left*: $\alpha = 3$, $\delta = 1$. *Bottom-right*: $\alpha = 3$, $\delta = 5$. Here $\alpha = 1$, $\beta = 4$, $\lambda_g = 1$, $\lambda_r = 2$, $a = b = 1$ and $x_0 = 0.5$

green adoptions, as expected, and they increase smoothly with increasing subsidies. The case of larger environmental damage is more complicated instead (right panels): When $\alpha = 1$ (equal impact on green and red adoptions) there is an unstable region of periodic dynamics for low subsidies amounts; when $\alpha = 3$ (unequal environmental damage for green and red adoptions) a strong non-linearity arises from increasing subsidies levels, with multiple equilibria and a tipping point. In this case, increasing subsidies have very little marginal effects on choices initially, until a critical value is reached and adopters jump from the unsustainable to the sustainable equilibrium with a vast majority of green adoptions.

Like in the previous section, we move to consider the alternative case of a milder environmental policy without taxes. Figure 7 reports the simulation in a scenario of relatively low Covid-19 impact. Here if green adoptions are affected more strongly by environmental damage, we observe almost no change induced by subsidies (bottom panels). If environmental damage affects green and red adoptions equally instead (top panels), there is a marked increase of green shares from increasing subsidies in a situation of low environmental damage (top-left panel). But in a situation of strong environmental damage, the same levels of subsides are characterised by very large oscillations of periodic dynamics. Such unstable outcome is the result of the minority game's negative feedback explained in the

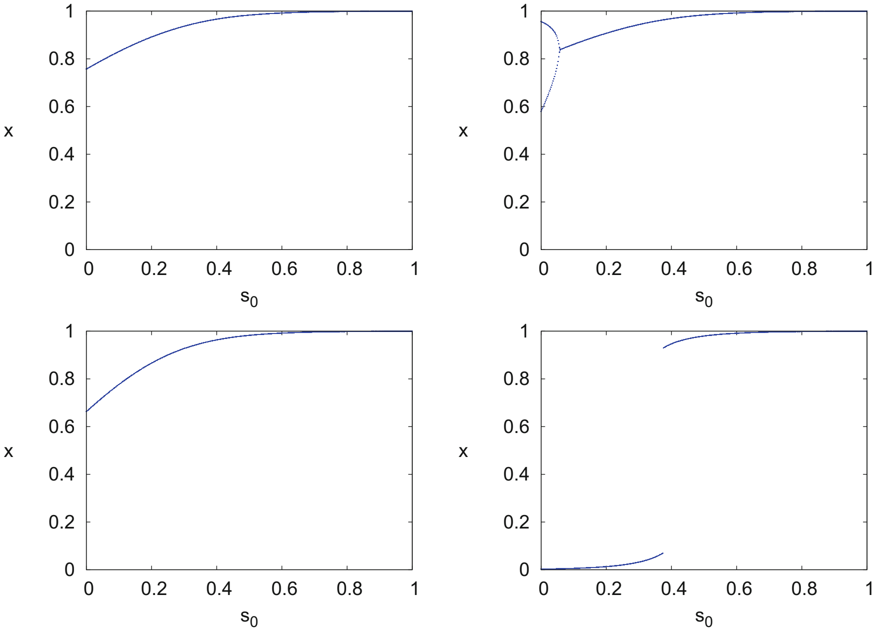

Fig. 6 Equilibrium value of the share of the green choices as a function of subsidies s_0. Strong policy mix with taxes and rebates $t_0 = 0.5$, $r = 1$. Scenario with relatively large Covid-19 impact, $v = 1$. *Top-left*: $\alpha = 1$, $\delta = 1$. *Top-right*: $\alpha = 1$, $\delta = 5$. *Bottom-left*: $\alpha = 3$, $\delta = 1$. *Bottom-right*: $\alpha = 3$, $\delta = 5$. Here $\alpha = 1$, $\beta = 4$, $\lambda_g = 1$, $\lambda_r = 2$, $a = b = 1$ and $x_0 = 0.5$

previous section, induced by a dynamic trade-off in the impact of Covid: Because of the substantially different damage of Covid-19 on choices, when green adoptions are more numerous, the damage on green adoption surpasses the damage on red adoptions, and the other way around.

The scenario of a relatively large Covid-19 impact is presented in Fig. 8. In this scenario, if environmental damage is small we observe a smooth increase in green shares from larger subsidies (left panels), but if environmental damage is large, we obtain periodic dynamics for large ranges of the subsidies parameter. In particular, small subsidies deliver periodic dynamics as an outcome of the minority game due to Covid-19 that amplifies environmental damage for green choices. As soon as a critical level of subsidies is reached, periodic dynamics leaves the place to convergence to a stable equilibrium with a vast majority of green choice.

Concluding, we observe that often a critical subsidies level exists to make the transition to a stable equilibrium where green choices are prevalent, which we can consider like the desirable outcome of a sustainability transitions. Depending on the scenario determined by the combination of environmental damage and Covid-19 impact, sometimes increasing subsidies produces a smooth increase in the share of green adoption, but there are conditions where for small subsidies either no appreciable effect is obtained, or instead Covid-19 induces a minority

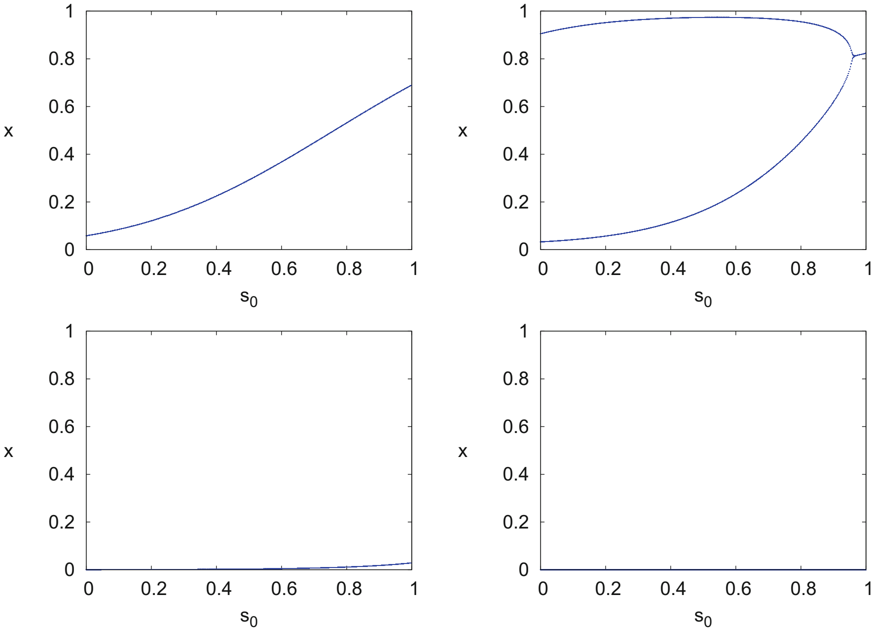

Fig. 7 Equilibrium value of the share of the green choices as a function of subsidies s_0. Mild policy mix without taxes $t_0 = 0$. Scenario with relatively small Covid-19 impact, $v = 0.1$. *Top-left*: $\alpha = 1$, $\delta = 1$. *Top-right*: $\alpha = 1$, $\delta = 5$. *Bottom-left*: $\alpha = 3$, $\delta = 1$. *Bottom-right*: $\alpha = 3$, $\delta = 5$. Here $\alpha = 1$, $\beta = 4$, $\lambda_g = 1$, $\lambda_r = 2$, $a = b = 1$ and $x_0 = 0.5$

game of choices with up and down dynamics of adoptions shares. We need to reach a critical level of subsidies for a stable larger share of green choices. In other words, a behavioural tipping point exists under Covid-19 to make the transition to a sustainable society.

4 Conclusion

The model shows that a transition to sustainability is possible under Covid-19 in scenarios where consumers' behaviour is driven by policies tailored on the Covid impact. However, the same impact of Covid presents dangerous outcomes where no transition takes place, or instead this impact is destabilising and creates undesirable periodic dynamics. The possibility of using the recovery response to the Covid-19 pandemic as a trigger of sustainability transitions depends very much on the policy interventions. The model shows how the role of policy is particularly crucial because of the non-linear response of the collective decision system to the factors involved (Covid-19 impact, policy interventions, environmental damage and the salience of environmental damage).

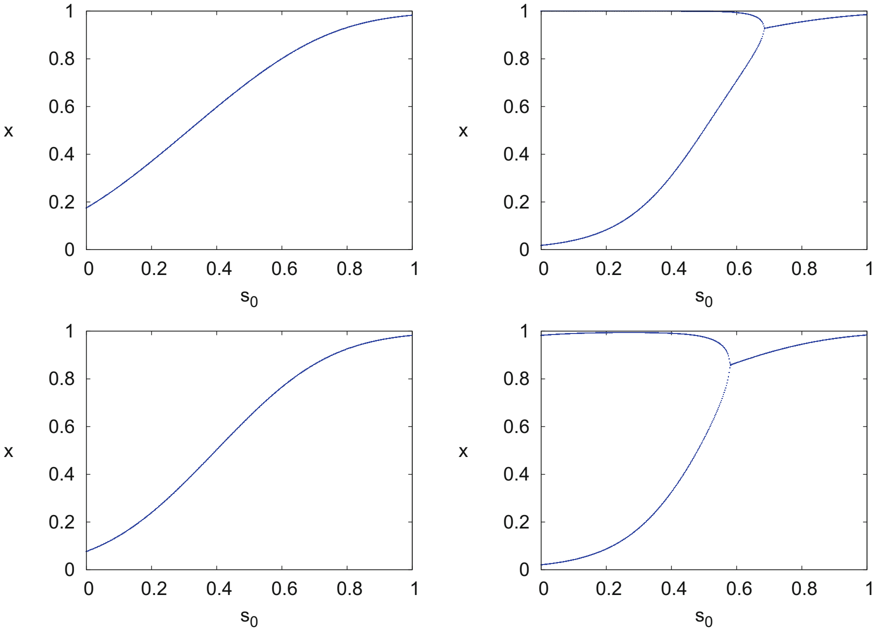

Fig. 8 Equilibrium value of the share of the green choices as a function of subsidies s_0. Mild policy mix without taxes $t_0 = 0$. Scenario with relatively large Covid-19 impact, $v = 1$. *Top-left*: $\alpha = 1$, $\delta = 1$. *Top-right*: $\alpha = 1$, $\delta = 5$. *Bottom-left*: $\alpha = 3$, $\delta = 1$. *Bottom-right*: $\alpha = 3$, $\delta = 5$. Here $\alpha = 1$, $\beta = 4$, $\lambda_g = 1$, $\lambda_r = 2$, $a = b = 1$ and $x_0 = 0.5$

This model is a first attempt to modelling mathematically the interplay between Covid-19, environmental damage and consumers' behaviour, and further analysis is necessary to study more in detail the different factors. For instance, the Covid-19 factor could be endogenised, because its impact depends on behaviours themselves to a good extent. A limitation of the model is to consider a unique decision dimension, and only to look at relative effects, not absolute ones. Also in this direction, further theoretical research is required.

The empirical validation of transitions models is difficult, because appropriate counterfactuals or control groups are impossible to obtain. Possibly and hopefully in a near future, survey data will be available at least to refine the model in order to offer a more precise description of the relevant mechanisms.

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Weather, Pollution, and Covid-19 Spread: A Time Series and Wavelet Reassessment

Olivier Damette and Stéphane Goutte

1 Introduction

Faced with the global pandemic of Covid-19, declared by the World Health Organization (WHO) on March 11, 2020, we need to better understand the behavior of the virus and especially its stability in different climatic environments. On a public policy point of view (sanitary, education, economic policies), it is crucial to evaluate the probability that the Covid-19 virus can decline or even disappear with Spring and Summer meteorological conditions. Though studies about survival times of the Covid-19 virus on surfaces are still under investigation, Bukhari and Jameel (2020) underlined that the spread of viruses depends upon environmental factors, with many respiratory pathogens showing seasonality and decreased transmission rates in warmer humid climates. According to models developed by Araujo and Naimi (2020), temperate warm and cold climates are more favorable to spread of the current Covid-19 virus.

Some researchers investigated empirically if climatic factors (temperatures, humidity, wind speed, solar radiation, etc.) could stop the spread of the epidemics. It is a legitime question regarding previous literature about the previous SARS virus. Chan et al. (2011), for instance, have shown that climate factors have probably impacted the outbreak of SARS—virus viability was rapidly lost at higher temperatures and higher relative humidity—and lead to different epidemics curves

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in countries with subtropical and tropical areas, also considering air-conditioned environments. This result is in line with previous studies concerning influenza (Dalziel et al., 2018) and previous SARS coronavirus (Casanova et al., 2010; Yuan et al., 2006) regarding the relationships between climatic factors, urbanization, and air quality and epidemics, suggesting that cold and dry conditions increase the transmission of the virus (Baker et al., 2020).

Without effective control measures, strong outbreaks are likely in more humid climates, and summer weather will not substantially limit pandemic growth.

However, the debate remains controversial: Wu et al. (2020) found effectively that high temperatures and high humidity should help to prevent the Covid-19 by reducing the transmission, but Jamil et al. (2020) do not find evidence of an association between high temperatures (up to 20 °C) and the spread rate. On a public policy point of view, this question is however crucial to better manage sanitary and quarantine policies according to the dynamics of the infected people. An effect of climatic factors could help authorities to stop the epidemics as a complement to sanitary policies. Recently, Hougeven (2020) indicated that there is a possibility that Covid-19 will be seasonal "going away" in May due to increasing pollen during Spring in non-tropical countries. So, what is the probability that weather changes impact the Covid-19 spread rate?

Air temperature and humidity are likely to directly impact the stability of the virus. But climatic factors are likely to impact the Covid-19 outbreak indirectly via air quality. Indeed, air quality, related or not to the meteorological conditions, is likely to impact the epidemics outbreak. Pollution is indeed a factor that is likely to perturb the immune system and thus increase the spread of infectious diseases (Caren, 1981; Bauer et al., 2012) like the coronavirus family. Ogen (2020) explained that the long-term exposure to highest NO_2 concentrations may be one of the most important contributors to fatality caused by the COVID-19 virus in some European regions in France, Italy, Germany, and Spain. In this way, lockdown policies are useful since they can also impact indirectly the Covid-19 outbreak by improving the air quality due to the strong induced reduction of emissions. For instance, Tobias et al. (2020) outlined the net improvement of air quality due to the lockdown in Barcelona.

A very recent empirical literature has emerged on this topic to test the links between climatic factors (temperature, wind, precipitations, solar radiation), air pollution, and the number of Covid-19 daily cases, but the results are not completely clear. If air quality and humidity seem to negatively and significantly affect the number of infected people, results about temperatures are less clear-cut. Heterogeneity of cases, samples, countries, or methods was probably one explanation.

Most of papers focused on China and suggest that the temperature variation and humidity may be important factors affecting the Covid-19 outbreak. Wu et al. (2020) found evidence, using cross-sectional and panel linear regressions, that high temperature and high humidity significantly *reduce* the transmission of Covid-19 in China. Ma et al. (2020) find a positive association between Covid-19 daily death counts and diurnal temperature range, but negative association for relative humidity. Xie and Zhu (2020) indicate that mean temperature has a positive linear relationship with the number of Covid-19 cases with a threshold of 3 °C, but they do not find clear evidence supporting that case counts of Covid-19 could decline when the weather becomes warmer. Qi et al. (2020) for Mainland China, from January 20, 2020 to February 11, 2020, assess the province-specific associations between meteorological variables and the daily cases of Covid-19 and find that temperatures and relative humidity showed significantly negative associations with Covid-19 with a significant interaction between them in the Hubei province. However, these associations were not consistent throughout Mainland China.

Furthermore, studies have been recently conducted for other countries and cities beyond China. Mohsen et al. (2020) reveal that precipitations and air temperatures have no effect on the Covid-19 outbreak in Iran. Coccia (2020) use data on 55 Italian province capitals and explained that the vast diffusion of Covid-19 in North of Italy is correlated with air pollution of cities measured with days exceeding the limits set for PM10 or ozone in previous years. Sahin (2020), for Turkey, conducted Spearman’s correlation tests by taking into account a 14-day incubation period and showed that the highest correlations were observed for wind speed 14 days ago, and temperature on the day, respectively. Very recently, Bashir et al. (2020) outlined that average temperature, minimum temperature, and air quality were significantly associated with the Covid-19 pandemic in New York based on Kendall and Spearman rank correlation tests, but they did not discuss the sign of their coefficients. Briz-Redón and Serrano-Aroca (2020) found no significant effects for Spain by incorporating control variables like non-meteorological factors such as population density, population by age, number of travelers, and number of companies.

However, as recently outlined by Baker et al. (2020), the relative importance of climate drivers is not fully characterized; with limited data on the current epidemic, these preliminary results are inevitably inconclusive. In this chapter, we reassess the relationships between local climatic conditions, air quality, and Covid-19 outbreak by developing an original time series analysis coupled with a wavelet study conducted on more than 100 time series observations. We consider two different provinces of China: Hubei as the original cluster and Beijing as a benchmark. The China case study is voluntarily chosen by considering the high number of available observations—higher than previous time studies—for this country in order to conduct a robust analysis and produce meaningful results. Wavelet analysis is more powerful than some other used methodologies, especially when applied on nonlinear and non-stationary data, like Covid-19 and meteorological series. Besides, large previous literature about China can be used as a valuable benchmark.

2 Data and Methods

2.1 Data

Our data set is composed of meteorological and air quality data and epidemiological data. We used daily counts of Covid-19 by downloading data from John Hopkins University Coronavirus Resource Center repository on May 5, 2020. Hence, we use a data set covering the January 20, 2020 to May 5, 2020 period and thus longer than previous studies.

The meteorological and air quality data include and were retrieved from the Air Quality Open Data Platform (https://aqicn.org/data-platform/covid19/). Concerning the weather variables Min, Max, and Average values for temperatures, pressure, and humidity indexes are considered. Concerning the air quality and pollution, we consider pm10, pm2.5, no2, and CO_2 variables. Again, we consider min, max, and average values of these variables. Indeed, extreme values like minimum temperatures might be more relevant to identify a potential link between weather and/or air quality and the spread of Covid-19 epidemics.

In addition, we only consider China case study for statistical robustness and sample size requirements. Indeed, statistical or econometric time series works are only relevant considering a sufficient number of observations for inference purposes. In our chapter, we consider 104 observations (from January 20, 2020 to May 5, 2020) that is a suitable sample to conduct a meaningful time series analysis.

2.2 Time Series and Wavelet Analysis

In this chapter, we proceed to a quantitative analysis by computing correlations and causality tests (Granger causality, see Granger, 1969) in a first step and performing a wavelet time series analysis in a second step. Though previous quantitative works have been conducted on different countries with more or less observations, we proceed to the first time to Granger causality and, above all, to a spectral wavelet analysis.

In contrast to standard or complex time series modeling (as the GARCH–DCC model), the wavelet coherence approach allows us to capture the co-movement between two time series in both the time and frequency domains. We adopt the wavelet coherence methodology by using the cross-wavelet transform and cross-wavelet coherence. The value of the wavelet squared coherence gives a quantity between 0 and 1, with a high value showing strong co-movement between time series and vice versa. However, unlike the standard correlation coefficient, the wavelet squared coherence only takes positive values. In this context, we cannot distinguish between positive and negative correlation. A solution is to use the phase difference of Torrence and Compo (1998) to provide information on positive and negative co-movements, as well as on causal relationships between time series.

Black arrows on the wavelet coherence plots indicate phase. A zero phase-difference means that the time series move together. The arrows point to the right (left) when time series are in-phase (out of phase) or are positively (negatively) correlated. An upward pointing arrow means that the first time series leads the second by $\pi/2$, whereas an arrow pointing down indicates that the second time series leads the first by $\pi/2$. A combination of positions is generally more common.

Wavelet has been previously used in environmental sciences, climate change issues, and very recently about Covid-19 issues (Iqbal et al., 2020). One property that gives interesting features for wavelet analysis, according to Gallegati (2018), is that wavelets are particularly suitable for analyzing complex signals, especially “no stationary, have shortlived transient components, have features at different scales, or have singularities” (see also Kumar & Foufoula Georgiou, 1997). The wavelet representation allows us to represent well both good time resolution at high frequencies and good frequency resolution at low frequencies. Wavelet and time series to analyze infectious diseases and weather have been previously discussed by Imai et al. (2015) for instance. Note that the wavelet methodology enables us to consider lagged effects of weather or air quality on Covid-19 outbreak and thus now well-known 14 days Coronavirus incubation period.

3 Results

First, as a benchmark, we investigate the potential association between meteorological factors and the number of Covid-19 cases by computing Kendall and Spearman correlations in the way of most previous studies. Our results reveal a positive association between temperature and daily Covid-19 counts for both Hubei and Beijing provinces in line with previous literature. Our results give strong significant results and are consistent for the two selected provinces. We find evidence of a negative correlation between humidity and daily cases of Covid-19. Therefore, our results confirm, in the vein of Qi et al. (2020) or Wu et al. (2020), that high levels of humidity affect negatively the spread of the virus. However, in line with most of previous papers, temperatures seem positively correlated with daily Covid-19 counts for both China areas: higher temperatures would be not a shield against the virus regarding only usual correlations.

Concerning pollution and Covid-19 relationships, our computations reveal a negative association between pollution indexes—CO_2, NO_2 emissions, P10 and P25, respectively—and the number of daily cases. Thus, our results seem empirically confirm that a bad air quality can aggravate the Covid-19 disease. However, as we will see, the relationship maybe a bit more complex. In addition, correlations have some limitations: if we go further of the problem of insufficient number of observations (we are working with 104 observations), correlations and regression frameworks do not take into account reverse causality problems. For example, a negative association between air quality and the number of infected people can be the consequence of the improvement of the air quality due to the lockdown policies implemented to reduce the high number of Covid-19 cases. The causality is thus not from air quality to Covid-19 declared cases but in the opposite way.

At second and more interestingly, we compute Granger causality (available online) tests for all pair-wise variables (note that we transform the Covid-19 daily cases in a stationary form to perform the Granger causality tests) and find some interesting discrepancies between Wuhan and Beijing. Considering different indicators of air quality (CO_2 emissions, PM 2.5 index), we find evidence of a causality link from air quality to Covid-19 daily cases in Wuhan. As a consequence, this result is corroborating evidence that bad air quality is likely to increase the intensity of the epidemics. However, this relationship does not hold for Beijing. This result can be related to Qi et al. (2020) that find different results concerning Wuhan and the rest of China.

In contrast, we derive a causality from Covid-19 daily cases to air quality indicators for Beijing. This result shows that the effects from the lockdown and economic downturn by drastically reducing the pollution have probably surpassed the bad direct effects of air pollution itself on the epidemics. In that way, our results also confirm and extend the previous results from Tobias et al. (2020) in Barcelona about the air quality improvement due to the epidemics. More generally, our results reveal that causality between air quality and Covid-19 epidemic is potentially bi-directional, more complex than previously identified, and can be of a completely different nature across different cities and situations (urbanization level, population density, economic development, etc.).

Finally, our basic causality results reveal a weak causality relationship between temperatures (average) and Covid-19 daily cases in Wuhan, epicenter of the epidemics, but not for Beijing. Nonetheless, this relation is relatively weak (only significant at 10% level) and can explain the controversial results about the temperatures–Covid-19 link in previous literature. Once again, this result suggests that relationships can vary across different local situations.

In addition, note that concerning a potential influence of humidity and atmospheric pressure on coronavirus diffusion, we do not find any significant causal relationship. It is thus impossible to confirm the negative association previously derived by correlation computations here and in previous literature.

Third, we next turn to a wavelet coherency (WTC) analysis between Covid-19 daily cases to check the robustness of previous results. The potential of this method (robust to non-stationarity, discontinuity, outliers) can be enlightening to go further of the previous analysis. Our results are presented hereafter via Figs. 1, 2, 3, and 4 (all results are available upon request). The horizontal axis refers to time, while the vertical axis refers to the period in days. The white line refers to the cone of influence, an edge below which wavelet power is affected due to discontinuity and, hence, difficult to interpret. The black contour denotes the 5% significance level. The level of correlation is indicated by the color on the right side of the charts; the hotter the color (moving from cool (blue) to hot (yellow)) the higher the absolute correlation value.

The coherency ranges from yellow (high coherency) to blue (low coherency) to measure the degree of co-movement. Thus, yellow color represents strong co-

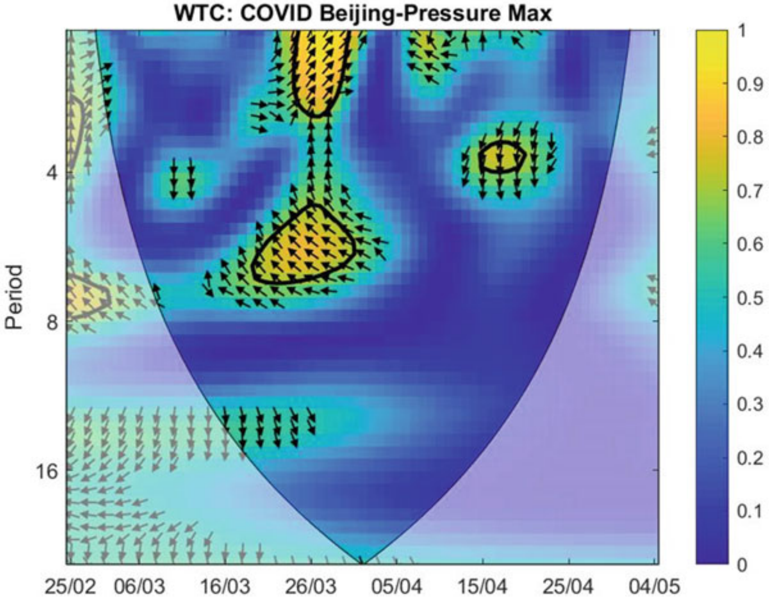

Fig. 1 Wavelet coherency (WTC) between COVID-19 daily cases and pressure in Beijing. Notes: The horizontal axis shows time, while the vertical axis refers to the period in days. The white line refers to the cone of influence, an edge below which wavelet power is affected due to discontinuity and hence, difficult to interpret. The black contour denotes the 5% significance level. The level of correlation is indicated by the color on the right side of the charts; the hotter the color (moving from cool (blue) to hot (yellow)) the higher the absolute correlation value

movement, whereas blue color corresponds to weak co-movements. We observe significant high degree of co-movements with Covid-19 daily cases and certain variables.

We can also identify the causality and phase. We recall that arrows indicate the phase differences between Covid-19 daily cases and the weather or air quality variables. For instance, a right arrow and a left one indicate that both Covid-19 daily cases and the weather or pollution variable are in phase and out of phase, respectively. Being in phase (out of phase) indicates a positive (negative) correlation. Moreover, an upper right or lower left arrow indicates that Covid-19 daily cases are leading, while a lower right or upper left arrow indicates Covid-19 daily cases values are lagging.

Let us now present our wavelet results. First, we do not find any clear relationship between pressure and Covid-19 daily cases in Wuhan, whereas we derive significant co-movements for Beijing around the end of March. If we look deeper on the results, we find that for the relationship between Covid-19 cases and atmospheric pressure in Beijing (Fig. 1), there is a significant period of coherence featured by co-movements in a short-run band (5 days to 1 week) for the period of March 20 to April 2. Moreover, the arrows are in majority upper left signifying an out of phase

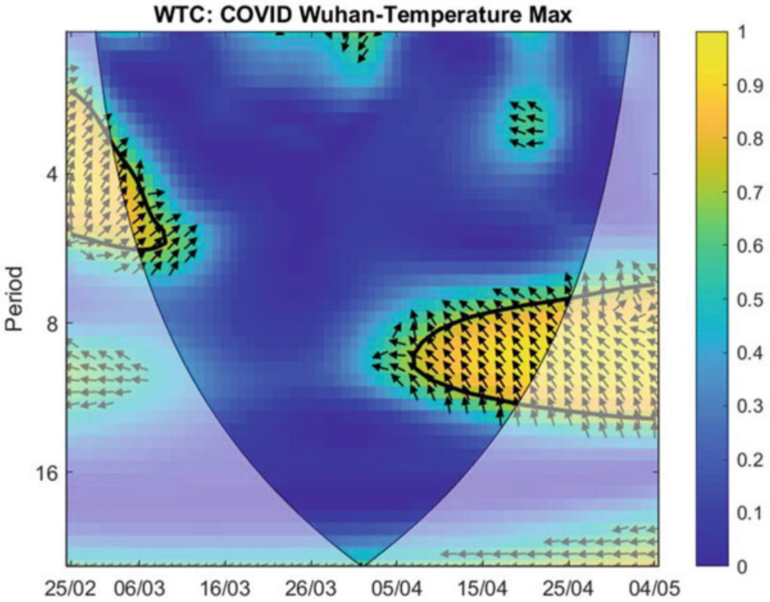

Fig. 2 Wavelet coherency (WTC) between Covid-19 daily cases and temperature in Wuhan

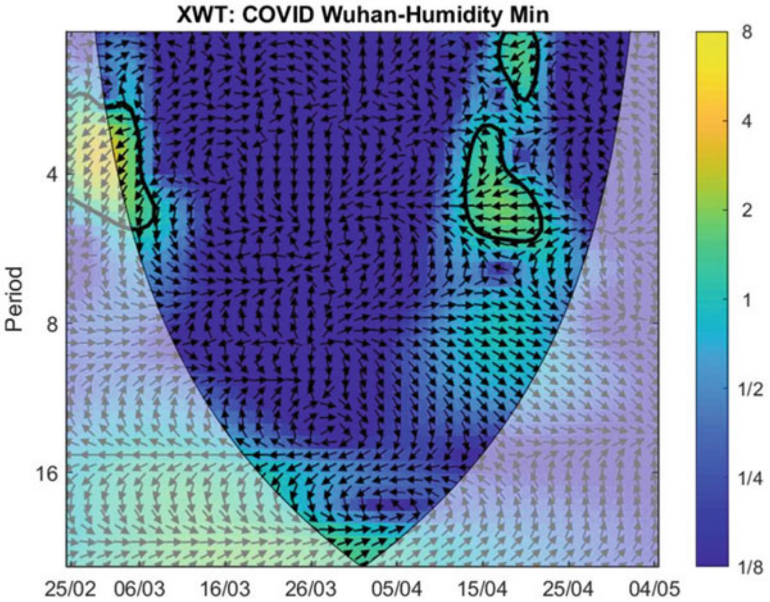

Fig. 3 Wavelet coherency (WTC) between Covid-19 daily cases and humidity in Wuhan

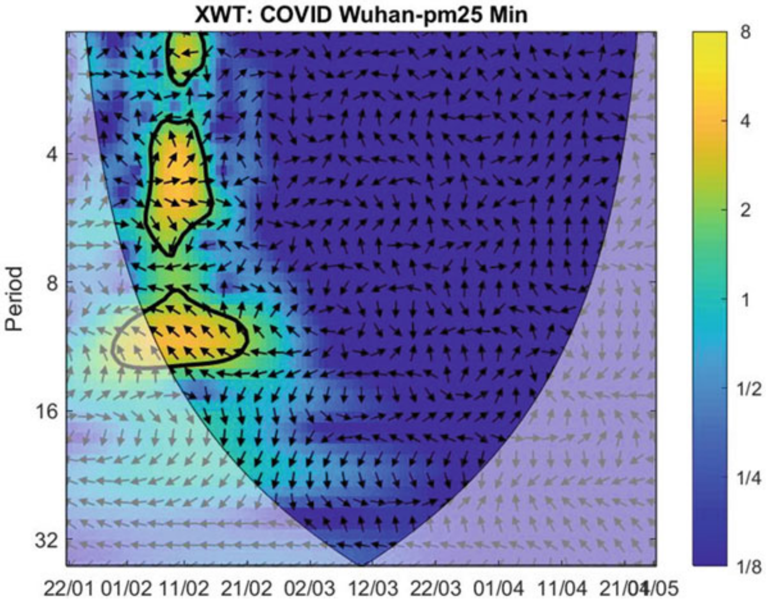

Fig. 4 Wavelet coherency (WTC) between Covid-19 daily cases and air quality (PM 2.50) in Wuhan

relationship and so indicating a negative correlation between Covid-19 daily cases and pressure values with Covid-19 values lagging those of pressure. This result is in favor of a significant pressure (maximum here) impact on the number of Covid-19 cases in Beijing.

Second, for the relationship between Covid-19 and temperature in Wuhan (Fig. 2), we outline a significant period of coherence with co-movements in the 1–2 weeks band for the period since April 6. Moreover, the arrows are in majority upper left signifying an out of phase relationship and so indicating a negative correlation between Covid-19 cases and temperature values with Covid-19 values lagging those of temperature. In other words, the relationship between temperature and Covid-19 epidemic seems to be really negative and not positive as suggested by correlations and previous results; this result seems more in conformity with theoretical predictions. However, it is more difficult to confirm this result for Beijing. Figure 3 presents the results about humidity for Wuhan and suggests only scarce significant co-movements. The results for Beijing (not presented here for space reasons) are not clear-cut as well. More generally, wavelet analysis about temperature and humidity shows that the relationship between weather and Covid-19 is complex and not uniform regarding time, frequency, and structural parameters across different cities and geographical areas.

Finally, concerning the relationship between Covid-19 and air quality in Wuhan (Fig. 4), we derive a significant period of coherence with co-movements in the 3 days to 2 weeks band for the period between February 3 and February 20. In fact, there are two different kinds of co-movements. The first one is related to a 3 days to 1 week frequency band, that is high frequency, with an in phase relationship that suggest a significant effect from the lockdown on air quality; the second one is related to a more longer band between 1 week and 2 weeks with an out of phase relationship for which the causality is working in the reverse case: better air quality is likely to reduce the number of infected people. This last result indicates a complex negative relationship between Covid-19 daily cases (and so lockdown) and air quality.

4 Conclusion

In the vein of Bukhari and Jameel (2020) and Baker et al. (2020), we share the idea that weather and especially warm and humid conditions will probably not be sufficient to curb the Covid-19 epidemics without suitable sanitary measures. Hence, higher temperatures and humidity will not be sufficient to stop the Covid-19 epidemics in Europe and North America. However, they are likely to marginally improve or deteriorate the situation, especially for vulnerable people considering variations of air quality.

For the first time, considering a robust time series dataset with 104 observations, we performed both correlations, Granger causality and spectral analysis via wavelet methods. We find that humidity is associated with a lower number of Covid-19 daily cases regarding correlation tests. This result was as expected and relatively clear in the previous literature. However, our causality and wavelet investigations are not clear on this question and do not reveal clear conclusion.

Besides, we more clarify the effect of temperatures on the virus. Though correlation coefficients between temperatures and Covid-19 cases are positive in line with some previous studies, we do not think that higher temperatures are an aggravating factor of epidemics. Indeed, wavelet analysis reveal that if correlation coefficients are positive in average, a significant causality relationship between temperature and Covid-19 daily cases can emerge in some periods outlining a negative causality from temperatures to the diffusion of the virus in Wuhan.

Our results also confirm that pollution and air quality, directly or indirectly, linked or not to weather conditions, are likely to impact the coronavirus spread. At the least, it seems to have been the case in Hubei. More interestingly, our Granger causality results show that the relationship can be heterogeneous across the cities and bi-directional. The downturn induced by the epidemics and the lockdown have also been air quality-improving and can interact or even dominate the previous relationship between pollution and Covid-19 spread. Wavelet results suggest that both effects coexist but at different frequencies. In the short run, the dominant effect goes from the lockdown on air quality; in a longer band, between 1 week and 2 weeks, the causality is working in the reverse case and better air quality induced by lockdown policies is likely to reduce the number of infected people.

Overall, wavelet analysis enables us to better investigate the relationships between meteorological, air quality, and Covid-19 spread by distangling frequency and time periods. They reveal complex relationships and suggest to investigate multiple causality links on both time and frequency dimensions. However, as most of statistical studies, there may be several caveats to our work, and we are aware that there are several other factors that may play roles in the number of affected cases. Epidemiological factors (population mobility, immunity, etc.), individual health factors and personal preferences (hygiene habits for example), and structural factors (urbanization and population density, public health infrastructures and policies, political and social preferences) should be incorporated in future works when large panel data sets will be available.

Further studies are expected to confirm or not our preliminary results and above all improve our understanding about the links between weather, pollution, and epidemics. Cross-country and long-run studies at a world scale will be necessary to further investigate the climate—beyond meteorological—impact on coronavirus and help to anticipate the emergence of other possible pandemics in the future. However, climate change and ecology transition issues are probably crucial topics to take into account in the epidemic's analysis.

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The Triple Climatic Dividend of COVID-19

Adel Ben Youssef

1 Introduction

Several measures in terms of mobility restrictions are adopted worldwide to prevent the spread of COVID-19. The crisis has slowed down the economic activity around the world by impacting each sector. At the same time, the overwhelmed hospitals with patients and increased number of infections have demonstrated that the resources of the health systems to be fragile and insufficient, with several bottlenecks, particularly in the underdeveloped countries (Chattu & Yaya, 2020). Besides these negative impacts of the crisis on the economy, the pandemic has brought several unexpected positive consequences on digital transformation, environment, innovation capacity, and structure of the governance. An unexpected positive effect on "biodiversity," "global warming," and "nature" is reported, resulting in a significant reduction of CO_2 emissions during the lockdown of 2020.

COVID-19 pandemic and climate change exposed the fragility of the global society to cope with shocks like natural disasters and pandemics. Both of them have a disproportionate impact on different communities (IPCC, 2014; Douglas et al., 2020; Botzen et al., 2021), thus intensifying inequalities worldwide. The impact of climate change and the COVID-19 crisis is felt more in the vulnerable population. Poor countries are more vulnerable to the effects of climate change since they are highly dependent on natural resources and their limited capacity to cope with climate variability and extremes. In the same way, COVID-19 impacts were more severe in the poor population. Not everyone has access to water, the main factor that helped in the prevention of the spread of COVID-19. This results in an increase

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of fundamental concerns about the sustainability of the way we are living (Tiba & Belaid, 2020).

There is a dual and complex relationship between human health and climate change (McMichael et al., 2008; Butler, 2018). The rapid ecological changes and severe effects of climate change may have led to the emergence of the COVID-19 pandemic. There is an ongoing debate about the relationship between COVID-19 pandemic and climate change, which is still conclusive. Several studies highlight the relation between COVID and environmental factors like temperature, humidity, and climate latitude (Shi et al., 2020; Poole, 2020; Guo et al., 2020; Chen et al., 2020). It is well known that the weather has a significant impact on respiratory infections (Sajadi et al., 2020; Wang et al., 2010; Ruiz et al., 2010; Vandini et al., 2013). The transmission of the epidemic could result due to the instability of the temperature, humidity, visibility, and wind speed (Chen et al., 2020). With increasing temperatures and human pressure on ecosystems, pandemic episodes of coronavirus or other types of viruses are expected to intensify in the future. The transmissions are made mainly with ecological vectors—water and/or insects. Environmental policies should emphasize the nexus of a healthy environment and public health policies.

This crisis could be a listening experiment on how to combat climate change. COVID-19 has raised awareness about the importance of changing human behavior since human activities significantly impact the environment. The change of the lifestyle during COVID-19 could help to shift toward a sustainable way of living. There is a lot of doubt about how long the new COVID-19 behaviors will last. Soon, people are expected to return to normal behaviors as before the pandemic crisis, and therefore, more actions need to be taken to maintain sustainable human behavior.

This chapter aims to explain the triple climatic dividend of COVID-19 by bringing three main contributions to the existing evidence. First, we discuss the reduction of global emissions as a result of the COVID-19 crisis. World emissions were reduced by 5.8% in 2020, but there exists the risk of the rebound of the emissions if the recovery is not sustainable (Belaïd et al., 2018, 2020). Second, we examine the impact of stimulus packages on climate change. Putting the green investment component in the recovery plans could lead to building back better and in a sustainable way. Third, we have found an important change in the behavior of people and the increase of awareness during the COVID-19 crisis. This change in the behavior of people has resulted in the improvement of the air quality and reduction of emissions. May this behavior change will be long-lasting, resulting in a sustainable future.

The chapter is structured as follows: Section 2 describes the major socio-economic impacts of the COVID-19 pandemic, Sect. 3 provides the analyses about the direct effect of COVID-19 on greenhouse gas (GHG) emissions, Sect. 4 discusses the green recovery plans and their impacts on climate change, Sect. 5 shows the change in the behavior of people during COVID-19 pandemic.

2 The Main Socio-Economic Impacts of the COVID-19 Pandemic in 2020 and 2021

The COVID-19 pandemic has affected most of the world's economies. Total containment policies during the first wave in 2020 have significantly impacted economic activity. Most of the world's economies are in recession, with significant repercussions in terms of job losses and loss of income for citizens. The recession in the world economy can be considered the "deepest" since the Great Depression of the 1930s.

After the first lockdown of spring 2020, several countries have reopened their borders. This reopening in May–June 2020 has led to the second wave of infections. Many measures and restrictions are taken to cope with the second and third waves of COVID-19 infections. This stop-go rhythm means that recovery is uneven and will take time to be back to "normality" again. According to the estimates of the IMF, the global economy experienced a contraction of −3.3% in 2020 and is projected to grow at 6% in 2021, moderating to 4.4% in 2022 (IMF, 2021).

COVID-19 has had a significant impact on international value chains. Several value chains exhibited discontinuities as some critical components for producing goods and services around the world are produced in China. Several countries were unable to produce basic goods and services. The crisis has shown that most countries depend on China for basic equipment and medicines. It is essential for the future to set up a "domestic sector" of health services in order to be able to react to any new wave of coronavirus. France, like several countries in the world, has adopted an "industrial policy" for basic drugs and medical equipment for the post COVID-19 period.

Many countries rely heavily on tourism, and the huge disruption caused by the pandemic is likely to increase other problems to capital flows, weak health systems, and limited fiscal space to allow the provision of support. In addition, some of these economies were already suffering from slow economic growth, which is likely to have major consequences in the near future. International arrivals dropped by 74% (UNWTO, 2020), due to an unprecedented fall in demand and travel restrictions worldwide. Global tourism has experienced the worst year on record in 2020, and the recovery remains still uncertain.

COVID-19 has devastating impacts on the labor market. Many businesses have reduced their activities temporarily in order to cut costs, and employees have been made redundant, asked to work from home or to work reduced hours. In the first quarter of 2020, around 5.4% of working hours were lost, compared to the fourth quarter of 2019. The estimate of overall working time lost in the second quarter of 2020 (compared to the fourth quarter of 2019) is 17.3%, or 495 million full-time equivalent jobs (ILO, 2020a, b). In 2020, 8.8% of global working hours were lost compared to the fourth quarter of 2019, equivalent to 255 million full-time jobs (ILO, 2020a, b).

COVID-19 has impacted the live conditions and well-being of many people worldwide. According to the World Bank estimates, COVID-19 has pushed between

119 and 124 additional people into extreme poverty, with around 60% living in South Asia. In 2021, the estimated poverty is set to rise to between 143 and 163 million (World Bank, 2021).

Vaccination of the population is accelerating, but the return to normalcy is not expected to happen soon, and a situation described as "new normal" seems to be happening. However, even with an effective vaccine, the concerns will continue to remain for a minimum of 1 or 2 years. Thus, cohabiting with the virus is the strategy adopted by many countries that will have to manage more or less a long transition period.

3 Direct Effect of COVID-19 on Greenhouse Gas Emissions

In the last few decades, the CO_2 levels were higher than at any time in the past 800,000 years (Lüthi et al. 2008). The last decade is considered the warmest decade on record during the past 150 years (Mann et al., 2016; Vitasse et al., 2018). According to NASA (2021), 2020 was the warmest year on record and saw a high decrease in global emissions due to the COVID-19 crisis.

Social distancing measures aimed at slowing the spread of COVID-19 have had a significant impact on the environment. The slowdown in economic activities has caused a drastic drop in greenhouse gas emissions, considered the most significant drop since World War II. Annual CO_2 emissions fell by an average of 4% during the Second World War (1939–1945), 3% during the 1991–1992 recession, 1% during the 1980–1981 energy crisis, and 1% during the 2009 Global Financial Crisis (Boden et al., 2017). Compared to the previous crisis, the decline of CO_2 emissions in 2020 is significant compared to major historical wars and epidemics (Pongratz et al., 2011; Boden et al., 2017).

The impact of the COVID-19 in the CO_2 emissions started to be felt at the end of February. In April, global emissions saw the most significant drop in many countries. Le Quéré et al. (2020) claim, in early May 2020, that daily global carbon emissions had declined by -17% from average levels in 2019. Global energy-related CO_2 emissions fell by 5.8% in 2020 (IEA, 2021).

However, the effect of COVID-19 on global emission reduction in 2020 could be short-lived. While the effects of the restrictive measures on the emissions were dramatic, the risk of the rebound of the emissions in 2021 is significant. IEA (2021) predicts that global emissions could increase by almost 5% in 2021.

3.1 Different Emission Reduction Across Countries

Bera et al. (2020) has examined the impact of COVID-19 lockdown on urban air pollution and amelioration of environmental health in Kolkata. They found that air was improved significantly during COVID-19, and they suggest implementing

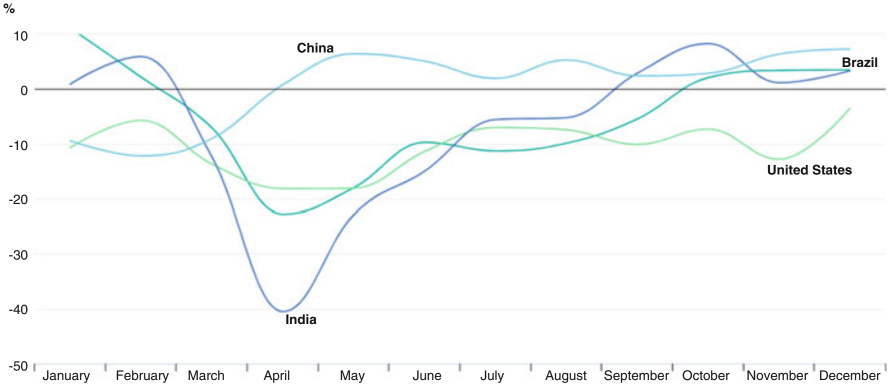

Fig. 1 Monthly evolution of CO_2 emissions in selected major economies, 2020 relative to 2019. (Source: IEA, 2021)

sustainable practices in the post-COVID-19 world. Li et al. (2020) have examined the impact of COVID on air quality in the Yangtze river delta region in China. They found a significant improvement in the air quality in this region. Similarly, Kerimray et al. (2020) found a significant reduction of CO, NO_2, and PM2.5 levels (by 49%, 35%, and 21%) during the lockdown period across Almaty, Kazakhstan compared with the previous year. According to IEA (2021), India has experienced the most significant drop in emissions during the lockdown of 2020.

However, after the first wave, measures started to be relaxed, and economic activity increased. This has resulted in an increase in emissions toward the middle of the year. The emissions continued to rebound also during the second half of 2020. In December 2020, global emissions were 2% higher than they were in the same month a year earlier (IEA, 2021) (Fig. 1).

3.2 *Transport Saw the Most Significant Drop in Emissions, While the Decarbonization of the Power Sector Has Accelerated*

Global emissions from sectors are reduced differently. Some sectors, like transportation and power production that have been hardly hit by the pandemic restrictions and measures, have contributed to a big drop in emissions.

Shan et al. (2021) have estimated the emission reduction according to the sectors. In their sample, they include 79 countries. According to their results, power and heating production and transport contribute most to emission reduction in 2020. The emission reduction in the power production sector is caused due to the decrease in demand for electricity from other sectors. The emissions of the transport sectors are reduced due to the big restrictions in the means of transportation, such as bus, railway, and flights.

According to IEA (2021), the transport sectors saw the most significant drop in emissions due to the COVID-19 crisis. Emissions from oil use in transport accounted for over 50% of the global drop in emissions in 2020. The restriction imposed on this sector resulted in about 14% drop in the emissions from this sector compared to 2019. Among the transport sectors that were hardly hit by COVID-19 is the aviation sector. Emissions from the aviation sector drop by about 45% in 2020, which was the level of the emissions seen in 1999. On the other hand, road transport was severely impacted, where the sales of cars declined about 15%, while the sale of electric cars was grown by more than 40% in 2020.

CO_2 emissions declined by 3.3% (or 450 Mt) in 2020 in the power sector. The power sector decarbonization has accelerated during this period. The COVID-19 epidemic encouraged increased investment in renewable energy in the first quarter of this year. The surge in renewable energy investment marks the industry's best first-quarter performance in a decade. Renewable energies maintained substantial investments in the entire 2020. The share of renewables in global electricity generation increased from 27% in 2019 to 29% in 2020, which is considered as the most considerable annual increase on record.

4 The Green Recovery Plans and Their Impacts on Climate Change

Countries around the world have launched economic stimulus programs to mitigate the effects of the COVID-19 pandemic. In total, governments have already announced nearly $12 trillion in fiscal stimulus in response to the COVID-19 health and economic crisis, more than three times the amount spent in response to the Great Recession of 2008–2009 (Dagnet & Jaeger, 2020). Details of spending remain largely unclear, and package estimates vary by institution.

The novelty lies in the magnitude of the environmental and climatic components. While the bulk of this funding will prioritize healthcare and direct support to the unemployed, around 30% of stimulus packages are spent on sectors that impact the environment and climate change. Most countries have adopted recovery plans, prioritizing policy choices that respect the natural environment and that would help achieve the sustainable development goals (SDGs). Stimulus packages have become a second chance to accelerate structural change toward low carbon economies, resilient to future shocks, and inclusive.

Several studies are discussing the impact of the recovery policies on the environment. Hepburn et al. (2020) have discussed the impact of the fiscal stimulus on climate change in G20 countries. They have proposed five main policies to be implemented in order to achieve the economic growth and climate goals: clean physical infrastructure, building efficiency retrofits, investment in education and training, natural capital investment, and clean R&D. Kroner et al. (2021) have discussed the recovery packages of different countries, and they highlight the importance of the actions for a green economic recovery putting policy climate actions in the center of the plan, in order to build back better and in a sustainable way. Forster et al. (2020) in their paper found that green stimuli is an important action, which led to the reductions in fossil fuel and could help to avoid additional global warming of 0.3 °C by 2050.

However, the recovery policies and plans are different around the world. While some countries have included a large investment in the green transition, in some other countries, environmental initiatives have been weakened. EU recovery plan has included a large number of green investments, even though the EU Green Deal could cause environmental damages elsewhere (Fuchs et al., 2020). The EU's green stimulus package can close the emissions gap between current policies and the ambitious 55% reduction target by 2030. The US has introduced their recovery plan of 1.9 trillion dollars, which is not clear for the investments in the green transition. However, the new government has pledged to put green policies at the heart of the actions, and this is demonstrated by the rejoining of the US in the Paris Agreement. South Korea, China, and India are planning green investments but are also supporting coal as part of their economic stimulus plans. However, strong commitments from South Korea toward carbon neutrality by 2050, from China for carbon neutrality by 2060 show that COVID-19 has accelerated the announcements of the ecological transition plans.

Governments have the option of putting in place "green" stimulus packages to accelerate structural change toward the low carbon transition. Designing stimulus packages with decarbonization goals in mind will help ensure a solid recovery and build a more sustainable growth path. National stimulus plans should be designed to enable countries to reap the benefits of the green transition, such as job creation, economic growth, and cleaner and resilient air (Heilmann et al., 2020).

The green stimulus can halve the accumulated global warming over the next 20 years. Significant disparities exist between countries and regions in terms of their ability to cope with both the pandemic and decarbonization. However, implementing suitable stimulus packages is essential for the low-carbon economy in the post-COVID-19 world.

5 Are Consumers Becoming Shifters?

Behavioral change is a crucial component in addressing both climate change and COVID-19 (Fischer et al., 2012; Engler et al., 2019, 2021). The period of COVID-19 not only reduced emissions but also changed consumer behavior and made citizens think more about ecological and sustainable issues. Coping with the spread of the COVID-19 requires significant challenges to address the social behavior values. In the same way, combating climate change requires addressing human behaviors.

The pandemic has affected almost every aspect of our lives. While some developments have been unexpected and unintentional, such as social distancing, wearing masks, banning public transport, travel restrictions, etc., other developments have accelerated the adoption of behaviors, such as the use of digital technologies, electronic commerce, e-work, and so on.

Several changes in consumer habits and behaviors were observed during the lockdown in the spring of 2020: a particular interest in health, a minimalist approach to consumption, an interest in purchasing and local production, an increase in the use of technology, and the increase in online shopping. These changes have resulted in emission reduction (Ben Youssef et al., 2020). Structural trends for eco-responsible purchasing behavior have been observed. Faced with supply chain disruptions, consumption has turned to local producers. Citizens are adjusting to spending more time at home and are expected to consume less outdoors while supporting their local producers. In addition, consumers are increasingly aware of the importance of consuming sustainable products.

The COVID-19 crisis also has affected incomes, forcing many to focus their spending on essential items. The closure of restaurants and food services has resulted in increased home cooking and more of a focus on healthy food and the potential consequences for the environment of purchasing activity. Many people are working remotely, and conferences have been held online using various platforms. Online activity has increased hugely during the COVID-19 crisis, with more online ordering, virtual tourism, online meetings, telemedicine, and distance learning; all trends that may continue after the COVID-19 crisis are over, which could result in more sustainable and eco-friendly consumption.

The awareness of the importance of the green and blue spaces is increased during this time (Rousseau & Deschacht, 2020), because when people feel a connection with nature and green spaces, they are more likely to spend time in them (Lin et al., 2014) and protect it (Schultz, 2002). Public green spaces are becoming appreciated to be visited. Moreover, urban green spaces have played a critical role in maintaining the physical and mental well-being of people (Samuelsson et al., 2020). Severo et al. (2020) found that COVID-19 is an essential factor impacting the behavioral change of people toward sustainability and responsibility.

The COVID-19 crisis has made clear the importance of the behavior to address climate change. More actions should be taken into the health and well-being of the global community in order to result in a long-lasting behavioral change (Betsch et al., 2020). In this matter, we should be concerned if these changes in people's behavior will be short-lived or long-lasting. The behavior of people may revert to the pre-pandemic patterns. As countries are recovering from the crisis, the behavior of people could be impacted by many factors. In this way, it is very important to take more actions to keep these changes in the long term. However, many of the long-term changes in consumer behavior are still forming, giving businesses the opportunity to help shape the next normal.

Environmentally friendly behaviors should be promoted in a post-pandemic world. These behaviors should be promoted at the local, national, and global levels and share values in the entire environmental ecosystem. Environmentally friendly activities should always be the main objective of the governments, in order to have a greener and greater way of living.

6 Concluding Remarks

This chapter aims to explain the triple climatic dividend of COVID-19: the reduction of global emissions as a result of the COVID-19, the impact of stimulus packages in climate change and the behavioral change of people, and the increase of awareness during COVID-19 crisis.

Lockdown during the first wave of COVID-19 had a positive impact on the environment, leading to a decrease in pollution and an improvement in air quality. This happened due to the shutdown of industries, aviation, and the downturn in the transportation sector in general. A reduction in commuting due to e-work policies has also played its part in reducing carbon emissions. This reduction was neither planned nor intentional, but in the end, it made it clear what could happen if no pro-climate action is taken. The reduction in emissions for the year 2020 is compatible with the achievement of the objective of the Paris Agreement.

Most countries have introduced their stimulus packages by prioritizing green policy choices that help promote environmental goals and accelerate structural change toward a low-carbon transition. Despite a wide variety of approaches, the stimulus packages indicate apparent changes in policy directions for the next decade. The investments made within the framework of these recovery plans show the principle of the double dividend: creating “green jobs” and respecting international commitments for the climate. This heralds a new post COVID-19 economic paradigm, which is substantial in terms of CO_2 emissions.

The response to this health crisis will determine how we deal with a climate crisis over the coming decades. Due to this pandemic, certain habits which are incidentally beneficial for the environment may persist even after its occurrence, such as the use of digital technologies, reduced travel, and reduced food waste. Maintaining this behavioral change could help in the transition toward a more sustainable world in the long term.

The recovery from the COVID-19 crisis should be green and sustainable. Investments should be redirected toward decarbonizing the economy and improving productivity for general well-being, as well as improving energy security, greater environmental and public health. Companies need to rethink their business models and should not revert to their usual “Business As Usual” practices. Covid-19 alone cannot change the profoundly unsustainable social and economic processes and practices that we have relied on for decades. Therefore, governments must act now and implement measures to achieve stronger environmental outcomes that can ensure economic prosperity, build resilience, and decarbonize the economy.

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COVID-19 and Cognitive Biases: What Lessons Can Be Learned to Fight Against Global Warming

Michelle Mongo

1 Introduction

The global economy is experiencing an unprecedented health crisis linked to the COVID-19 virus. Almost 1,086,274[1] deaths have been recorded worldwide, and around 38,138,374 reported cases. On January 30, 2020, the World Health Organization recognized the public health emergency of international concern in the face of the spread of COVID-19.[2] Despite this, populations have misidentified the exponential growth in the number of COVID-19 cases, which has led to a late response from public authorities (Kunreuther & Slovic, 2020). In France, for example, on March 5, 2020, 47% of French people said they were worried about the virus, but 53% of them did not wash their hands after taking transport, 75% continued to shake hands, and 91% kissed their relatives again (Ifop, 2020). For Meyer and Kunreuther (2017), this rather paradoxical behavior is attributable to cognitive biases (such as myopia, amnesia, optimism, inertia, simplification, and the herding mechanism) that lead individuals to play the "ostriches" in other words, to deny the obvious risky situations. These biases explain the lack of preparation of individuals in the face of crisis situations (Kunreuther & Useem, 2009; Robinson & Botzen, 2019).

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[1] As of 10/14/2020. Source: https://coronavirus.jhu.edu/map.html

[2] https://www.who.int/news/item/30-01-2020-statement-on-the-second-meeting-of-the-international-health-regulations-(2005)-emergency-committee-regarding-the-outbreak-of-novel-coronavirus-(2019-ncov)

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With regard to the management of the COVID-19 crisis and exceptional health[3] (Bol et al., 2020; Wang et al., 2020) and economic[4] (Herrero & Thornton, 2020) measures put in place by many countries, it can be particularly interesting to wonder about the parallel that can be drawn with the management of the climate crisis and to draw lessons from it to combat global warming (Kunreuther and Slovic 2020; Manzanedo & Manning, 2020). Indeed, despite the many IPCC reports warning of the consequences of our human activities on the planet (IPCC, 2018), CO_2 emissions keep increasing, increasing the window of action making it possible to limit the global temperatures rise to 2 °C or even 1.5 °C above pre-industrial levels by the end of the twenty-first century (UNEP, 2017).

As opposed to inaction, the unprecedented health and economic measures put in place by governments to limit the spread of the COVID-19 virus and boost their economies can be seen as a rapid experiment of how to combat the climate crisis (Botzen et al., 2021). On the one hand, these measures show that large-scale economic actions are possible and on the other hand that changes in consumption and production patterns centered on essential needs are possible, as well as priority for strategic sectors such as education and health, which make it possible for all to guarantee social justice and more sustainable development of our economies.

Obviously the positive impacts on the climate[5] (Achebak et al., 2020; ESA, 2021; IEA, 2020) are only temporary because they do not reflect the structural changes of the world economies (Le Quéré et al., 2020).

Therefore, the question is how to move toward more sustainable development in a post-COVID-19 situation to effectively fight against global warming. For Ibn-Mohammed et al. (2021), the solution involves the development of a circular economy which allows us to move away from a traditional logic of linear economic development aimed at "producing, consuming and disposing" to move toward economic development, which tends to limit the waste of resources and the environmental impact while increasing efficiency at all stages of product economy. From this point of view, the opinions of experts diverge and crystallize on certain circular economy principles that would be sources of CO_2 emissions. For example, Stahel (2014) recognizes that among the 3Rs, reuse is the principle of the circular economy that has the most impact on the environment and climate. Eco-efficiency strategies induced by the reduction principle and characterized by an increase in the productivity of companies have the effect of generating rebound effects which increase the use of resources (Font Vivanco et al., 2016; Ness, 2008). In short, it is urgent to find a consensus on the best strategy to adopt between "efficiency and sufficiency" in order to limit the consumption of resources and CO_2 emissions

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[3] Wearing a mask, social distancing and confinement of populations.

[4] As of April 22, 2020, the amount allocated by governments around the world to stimulate economies in the face of the consequences of the health crisis (containment measure) is estimated at nearly 8.4 billion dollars, the vast majority of which is linked to tax measures (94%).

[5] Linked to the decline in economic activities caused by confinement.

(Figge et al., 2014). In this sense, the circular economy must be placed in a context of taking into account planetary limits in order to be as relevant as possible.

This chapter aims to provide an analysis allowing a better understanding of the main cognitive biases behind the management of the COVID-19 crisis to draw lessons for the fight against global warming.

Thus, we will first present the main cognitive biases at the origin of the lack of preparation of individuals in the face of crises such as the COVID-19 crisis. Then we will present the issue of this type of behavior with regard to environmental and climate issues. After that, we will present the lessons in terms of public policies for climate change mitigation and adaptation that can be drawn from the exceptional health and economic measures put in place by governments to limit the spread of the COVID-19 virus and stimulate economies. Finally, we will discuss the possible economic development prospects in the post-COVID-19 situation in order to ensure more sustainable development of our economies.

2 Cognitive Biases: Management of Health and Climate Crises

2.1 Chronology of Health and Climate Alerts

Numerous alerts attesting to a COVID-19 epidemic were issued during the early stages of the virus spread. It is not a question here of drawing up an exhaustive list of these alerts but only of presenting the main alerts launched and which led to the scale of the epidemic being taken into account.[6]

One of the first alerts began on January 5, 2020, with the WHO reporting of cases of 44 patients with pneumonia of unknown etiology detected in China by national authorities. On January 13, 2020, Thailand reports the first case of COVID-19 outside China detected in a woman from the Wuhan region. After 10 days, on January 23, 2020, the Chinese government decides to confine tens of millions of people in the Wuhan region. But the epidemic continues to spread, and on January 24, 2020, nearly 830 cases were diagnosed in nearly nine countries (China, Japan, Thailand, South Korea, Vietnam, Nepal, and the United States). On January 30, 2020. On March 11, 2020, given the alarming level of spread and severity of the disease, the WHO estimates that COVID-19 can be classified as a pandemic.

Along with these various alerts, in France, for example, on March 5, 2020, 47% of French people said they were worried about the virus, but 53% of them did not wash their hands after taking transport, 75% continued to shake hand, and 91% still kissed their loved ones (Ifop, 2020).

Likewise, several dates marked the alerts concerning planetary limits and global warming on the climate and environmental side. These have emerged through the

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[6] https://covidreference.com/timeline_fr

different dynamics that have animated the concepts and institutions of sustainable development. One of the first alerts was part of the report (Meadows et al., 1972) commissioned by the Rome club and which warned of the depletion of raw material resources. Following on from the Meadows report, 1972 also marks the holding of the first United Nations conference devoted to environmental issues, the Stockholm Conference. Within this framework, the environment takes on an international status, and a program is created, the United Nations Environment Program (UNEP). During the preparation of the conference, which was to mark the 20th anniversary of the Stockholm conference in 1992, developing countries refused to allow environmental constraints to prevent their development. Mrs. Brundtland was then given the mandate to chair a preparatory commission that will propose the concept of sustainable development and which envisages reconciling development with the limits of the planet. This proposal is endorsed by the Rio + 20 conference, which will set a program, Agenda21, and a follow-up process for the "Commission for Sustainable Development." A chapter is devoted to local authorities, which are committed to implementing these programs through local Agendas 21.

Three conventions are also signed in Rio and will have their own monitoring process: the Conferences of the Parties (COP). They are independent of sustainable development processes. The Millennium GA in 2000 will set the Millennium Development Goals, the MDGs. They focus on poverty without coordination with sustainable development. The Johannesburg conference in 2002 will consolidate the sustainable development agenda and launch processes such as the one on sustainable consumption and production. In countries, sustainable development strategies compete with poverty reduction strategies, which are the only ones financed. We will have to wait for the Rio conference in 2012 for the connection to be made with the development process. The 2015–2030 action program will therefore target sustainable development objectives. Seventeen goals are defined by the UN and aim to fight collectively for the preservation of the environment, global warming, and social inclusion. The United Nations Framework Convention on Climate Change (UNFCCC) is exemplary in its relationship with scientific and academic institutions. It is the Intergovernmental Panel on Climate Change (IPCC/IPCC), created in 1990, which serves as the scientific basis for political decisions taken in the governing body of the Convention: the Conference of the Parties (COP in English). The conventions signed in Rio have, like all conventions, their own decision-making process; only the countries which are "parties" to the convention contribute. While the processes under the auspices of the United Nations (i.e., the General Assembly or the Economic and Social Council, ECOSOC) involve all member countries, the conventions only bind those signatories that have ratified the convention and its protocols. This explains the separate approaches between the universal framework for sustainable development and SDG 13 Climate.

Relying on climate models, the IPCC will demonstrate the need to limit warming to 2 °C, which implies limiting the concentration of greenhouse gases and therefore global emissions. But it is the mechanism of the convention that will set these objectives and their national distribution. Once these commitments have been ratified, the countries will translate them into policies, laws, and regulations, communicate in order to mobilize the country's stakeholders, and allocate resources through tax incentives, for example. COP21 is the most significant of the conferences of the parties. Indeed, the Paris agreement on climate change in 2015 is signed by almost all the countries of the world. They pledge to keep the global average temperature rise "well below" 2 °C above pre-industrial levels and "to continue to take action to limit the rise to 1.5C." However, since the Paris Agreement, emissions have continued to increase (UNEP, 2017). How to explain this paradox?

2.2 Cognitive Biases and Error of Assessment in a Crisis Situation: Comparative Elements

Human behavior in the face of risk is complex and far from being limited to a rational logic of "homo oeconomicus" guided by its desire to maximize its utility at a lower cost (Mongin, 2002; Kahneman & Tversky, 1979). Professional psychologists are the first authors to have demonstrated the important role of cognitive psychology in the decision-making process of individuals. According to these authors, the decision-making process of individuals is guided by subjective considerations primarily linked to their cognitive system. Indeed, the human cognitive system has an architecture capable of processing information according to two operating modes (Gollier et al., 2003). The first mode of operation is rapid and based on automatisms and mechanisms that are not very conscious. The second, conversely, is slower and "cognitively more expensive" because it requires attention, reasoning, logic. Because of its high cognitive cost, the second mode of operation is not often deployed in everyday life, which suggests that the decisions of individuals are in the majority of cases taken by a cognitive mode of operation that has been removed from all rational logic (Gollier et al., 2003).

For Meyer and Kunreuther (2017), these cognitive biases can be expressed in six possible ways:

1. Myopia: a tendency to favor urgent short-term risks at the expense of a longer-term analysis.
2. Herdind mechanism: a tendency to base one's own choices on observing the choices of others.
3. Amnesia: a tendency to forget too quickly the lessons of past disasters.
4. Inertia: a tendency to favor inertia at the expense of alternative protection measures.
5. Optimism: a tendency to underestimate the probabilities of losses associated with a risk situation.
6. Simplification: a tendency to deal selectively with only a set of relevant factors to be taken into account when making risky choices.

The author admits that these different biases largely influenced the lethargic behavior of individuals and the inertia of public decision-makers during the early stages of the COVID-19 crisis. Botzen et al. (2021) add that in view of these different biases, a parallel can be drawn between the management of the COVID-19 crisis and that of the climate crisis. The example of the myopia bias illustrates this parallel perfectly. In fact, the myopia bias assumes that individuals favor urgent short-term risks at the expense of long-term investment to limit the risks. In a COVID-19 health crisis, this cognitive bias characterized by the perception of an immediate and urgent risk explains the consent of individuals to drastic health measures imposed by governments (wearing a mask, social distancing, and sanitary confinement) (Bol et al., 2020). This cognitive bias also explains the low level of investment in climate change adaptation and mitigation measures, the effects of which are perceived in the longer term and therefore less urgent.

Botzen et al. (2021) complete these analyzes by showing to what extent the management of the COVID-19 crisis and the climate crisis are also influenced by means of "finite pool worry," "availability," and "not in my term of office."

The "finite pool of worry" bias assumes that individuals cannot simultaneously worry about too many problems. There are some issues that will be the subject of more concern for individuals. Botzen et al. (2021) thus assume that given the disastrous health and economic consequences caused by the COVID-19 crisis, individuals will tend to postpone their level of worry toward the COVID-19 crisis until depends on the climate crisis. The climate crisis will return to the heart of people's concerns when the consequences are perceptible and immediate but irreversible.

Availability bias refers to a situation where the individual evaluates a given risk based on their experience with that risk. The risk is all the more underestimated as the lived experience is low (Tversky & Kahneman, 1973). This bias has been the subject of numerous empirical studies, and in the context of climate change, Spence et al. (2011) show that individual perceptions of climate risk and the adoption by individuals of measurement mitigation and adaptation are positively correlated with natural disaster experiences (flood, hurricane, etc.). For its part, concern about COVID-19 will be all the more significant as the individual in their immediate environment will be confronted with the risk of infection from the virus.

Finally, the "not in my term of office" biais refers to the attitude adopted by politicians and which aim to postpone the investment allowing to limit the potential risks in the long term in favor of more visible investment during the short term of the electoral mandate (Kunreuther & Useem, 2009). The purpose of such a move is to secure eventual re-election. However, in the event of a situation such as global warming, public decision-makers must act quickly by favoring economic development trajectories focused on sustainable development. They must invest heavily in adaptation and mitigation measures in order to preserve the future of our present and future generations. However, despite the climate emergency, investments in favor of the climate are still too low. Indeed, at the end of the 21st Conference of the Parties to the United Nations Convention on the Fight against Climate Change held in Paris in December 2015, the industrialized countries pledged to provide annually and from 2020 the amount "floor" of $100 billion to help developing countries fight climate change and adapt to new conditions.

The report (Oxfam, 2020) estimates the commitment of industrialized countries to help developing countries fight climate disruption at just $59.5 billion per year in 2017–2018. For Healy and Malhotra (2009), the underinvestment of public decision-makers in climate change adaptation and mitigation measures such as natural disaster preparedness is linked to the fact that voters reward politicians who provide financial assistance after the disaster rather than those who invest in disaster prevention measures.

The shortage of supply of masks during the first phases of the COVID-19 crisis as well as the containment measures that were subsequently imposed did not prevent voters from consolidating the position of elected officials already in place. Based on a survey carried out over the period of March–April 2020 among voters in Western Europe, Bol et al. (2020) show how health restrictions such as confinement increased voting intentions for the political parties in place (prime minister/president), thus reaffirming their confidence and satisfaction in favor of the government in place.

These biases invite us more than ever to be vigilant in limiting the risks of emergency management of health and climate crises.

However, it should be recognized that the exceptional economic and health measures put in place by governments to limit the spread of the COVID-19 virus and stimulate economies are all examples that show that large-scale, collective, and rapid action is possible to fight against global warming. Herrero and Thornton (2020) show that nearly $8.4 trillion was released by governments in just 10 weeks to stem the spread of COVID-19. About 94% of these funds have been earmarked for tax measures to boost savings, and the rest is linked to investments in health services and vaccine development. The health measures put in place (containment, opening of essential trade) thus show that changes focused on essential, local consumption, and production patterns are possible and allow more sustainable development.

Must we conclude from this that the COVID-19 crisis constitutes an opportunity for the climate?

3 The COVID-19 Crisis: An Opportunity for the Climate?

3.1 Impact of the COVID-19 Crisis on the Environment and Climate

Greenhouse gas emissions are responsible for nearly 95% of global warming (IPCC, 2018). The most important greenhouse gas is carbon dioxide (CO_2). Carbon dioxide is generated by the use of fossil fuels such as coal, oil, or gas. The sectoral breakdown of CO_2 emissions provides information on the most polluting activities and at the origin of global warming. Thus we observe from data provided by the International Energy Agency that in 2016, electricity production remains the leading CO_2 emitting sector in the world, with 40% of total emissions due to the combustion of gas energy. The other two major sectors contributing to emissions are transport

(24%) and industry (19% including construction). In China, industry and the energy sector (electricity and non-electricity) account for a larger share of CO_2 emissions compared to the world average.

In the spring of 2020, a period during which the first containment measures were implemented in many countries around the world (countries in Europe, North America, and Asia), global energy demand fell by nearly 3.8% (IEA, 2020). Daily data analyses carried out by the IEA (2020) show that countries having adopted strict containment measures show a drop of nearly 25% in energy consumption per week compared to 18% for countries having adopted measures of partial containment. Among the energy sources consumed, coal is the energy source most strongly impacted by the health crisis, with a drop in global demand of nearly 8% compared to the first quarter of 2019. This drop is explained by the health situation in China during this period.

Indeed, China was one of the first countries to implement strict containment measures, which shut down a large part of the country's economic activity, whose main energy source is based on the use of coal. For its part, oil demand fell by nearly 5% during the first quarter of 2020. This drop is explained by restrictions on mobility (travel by vehicle, plane) imposed by the containment measures. The transport sector accounts for nearly 60% of global oil demand and is responsible for nearly 25% of CO_2 emissions. Finally, gas has experienced a more moderate decline, around 2% over this period. Only renewable energies show growth rates in demand during this period. According to IEA (2020), these changes should contribute to a significant drop in CO_2 emissions during 2020. Le Quéré et al. (2020) confirm these forecasts by showing to what extent the original CO_2 emissions fossils have seen a record drop of nearly 7%, largely due to containment measures. This year-to-year reduction is one of the largest ever recorded in nearly 10 years (IEA, 2020).

These containment measures have also had beneficial effects on air quality. Indeed, satellite observations made by researchers from the National Aeronautics and Space Administration and the European Space Agency (ESA, 2021; NASA 2020a, b) show a significant drop in the level of air pollution over many countries (as in China or France for example) during the containment period of spring 2020. Nitrogen dioxide (NO_2) is a harmful gas mainly resulting from the combustion of gasoline, coal, and fuel from diesel vehicles. This gas has the particularity, when it is near the ground, of transforming into ozone, which makes the air cloudy and difficult to breathe. However, during the period 10–25 February, observations by NASA (2020a, b) show a significant drop in the level of nitrogen dioxide in China but also in India and Bangladesh. In Europe, similar trends are observed during this period (ESA, 2021). The following maps show the level of nitrogen dioxide concentration in Europe during the periods of March–April 2019 and March–April 2020. It thus appears that the average concentrations of nitrogen dioxide between the two periods have fallen sharply in Europe: Madrid, Milan, and Rome show decreases in average nitrogen dioxide concentrations of around 45% over the two periods while Paris records a decrease of nearly 54%. These disparities are largely linked to the strict containment measures operated in Paris during this period (Fig. 1).

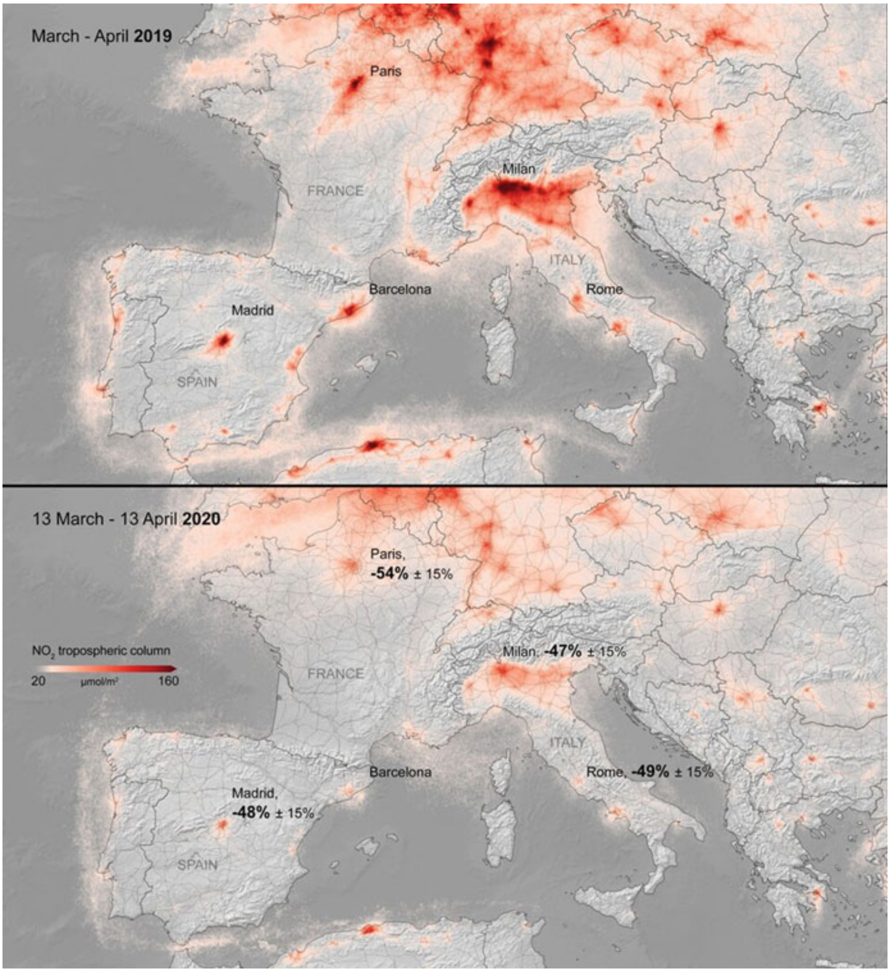

Fig. 1 Nitrogen dioxide concentrations over Europe (ESA, 2021)

However, despite the possible benefits of the climate-induced by containment measures which have forced the shutdown of a large part of economic activity in the world, this situation is only temporary because it does not reflect structural changes in global economies (Le Quéré et al., 2020). Le Quéré et al. (2020) warn of possible "rebound effects" linked to the upturn in economic activity. The latter would then erase the effects caused by the containment measures. Satellite observations made by NASA (2020c) 3 months after the February 2020 containment period in China show a return to "normal" levels of nitrogen dioxide pollution in China during this period of the year. The rebound effect feared by specialists is already noticeable.

So how can we move toward more sustainable development in a post-COVID-19 situation in order to effectively fight against global warming. For Ibn-Mohammed et al. (2021), the solution goes through the development of a circular economy, which makes it possible to move away from a traditional logic of linear economic development aiming to “produce, consume and throw away” to move toward economic development, which tends to limit wastage of resources and environmental impact while increasing efficiency at all stages of product economy. The following section proposes to present this concept and to discuss the conditions for its implementation.

3.2 The Circular Economy: A Solution for a Sustainable Development Post-COVID-19?

The circular economy is most often represented as a combination of three principles, namely the reduction, reuse, and recycling of activities (also called the 3Rs) (Kirchherr et al., 2017).

- The reduction aims to minimize the use of energy, raw materials, and water as close as possible to the source, in particular, to reduce the generation of waste or polluting emissions. It is based on the concept of cleaner production as a proactive approach to environmental strategies. In addition, it is based on two approaches, “eco-efficiency” and “resource efficiency.”
- Reuse brings together all the operations allowing waste to be used again to give it a second life, whether the use is identical or different (Article L541-1-1 Created by Ordinance n ° 2010-1579 of December 17, 2010 - art. 2).
- Recycling corresponds to “any recovery operation by which waste is reprocessed into products, materials or substances for the purposes of their initial function or for other purposes. This includes the reprocessing of organic material but does not include energy recovery, conversion for use as fuel or for backfill operations,” according to European Directive 2008/08/EC.

In accordance with these principles, the French Ministry of the Environment in charge of international relations on climate change positions itself on the circular economy through ADEME’s definition: “an economic system of exchange and production which, at all stages of the life cycle of products (goods and services), aims to increase the efficiency of resource use and reduce the impact on the environment while developing the well-being of individuals” (Magnier et al., 2017).

The circular economy is a strategy of the European Commission (2019), enabling it to achieve a carbon-neutral economy by 2050. Indeed, “the action plan for a circular economy” (European Commission, 2014) aims to accelerate the decoupling of EU member states. As for the literature on the circular economy, most of the work focuses on the “substance” of the circular economy, in other words, on the different principles and methods and the way in which they must be implemented at different scales (micro, meso, and macroeconomic) (Ghisellini et al., 2016). In this context, the circular economy is considered beneficial for the environment and the climate. This result is evaluated through different accounting tools (material flow analysis, life cycle analysis, residual materials management, eco-design, etc.), which make it possible to account for the impact of the consumption of resources on the environment.

Indeed, these indicators rarely have a macroeconomic scope. When they do, e.g., material flow analysis, the dynamic relationship between CO_2 emissions and macroeconomic indicators is not often explored. More recently, Vuţă et al. (2018) proposed an econometric study aimed at assessing the impact of the circular economy on the economic growth of EU member countries. The results of this study show to what extent the circular economy has a positive effect on the economy of EU countries. The authors conclude that a circular economy is an excellent tool for moving toward more sustainable development in Europe. However, Mongo et al. (2021), in a recent study, examine at the European Union level the impact of the circular economy on CO_2 emissions in Europe over the period 2000–2015. The study results show that in the long term, the sustainable management of resources tends to lower CO_2 emissions in Europe. While in the short term, the demand for material extraction triggered by the consumption and investment of households, governments, and businesses in the EU as well as the total quantity of materials directly used by European economies, contribute to the increased CO_2 emissions. Only the recycling of municipal solid waste tends to lower CO_2 emissions in Europe. These results show to what extent the demand for material extraction triggered by the consumption and investment of households, governments, and businesses in the EU as well as the total quantity of materials directly used by European economies are still too high and therefore contribute to an increase in CO_2 emissions in the short term.

So how can we explain, in light of these results, the negative influence of the short-term circular economy on CO_2 emissions?

From this point of view, many expert opinions diverge on the supposed impact of the circular economy on the environment and the climate. The main differences concern certain principles of the circular economy, which are supposed to be sources of CO_2 emissions. Stahel (2014) recognizes that of the 3Rs, reuse constitutes the principle of the circular economy which presents the most in terms of impact on the environment and the climate. The principle of reduction is based on eco-efficiency strategies characterized by an increase in the productivity of companies. For Ness (2008), these mechanisms have the effect of generating rebound effects that are sources of increased use of resources. Today the material footprint is still too large, and data from the Global Footprint Network shows that in 2016, the lifestyle of a North American required 4.95 planets compared to 2.8 for a European and 0.83 for an African. Recycling, on the other hand, is the least sustainable principle of all circular economy activities in terms of profitability and resource efficiency (Stahel, 2014). The study carried out by Graedel et al. (2011) and aimed at evaluating the relevance of metal recycling processes confirms the limits of the recycling process in this sector due to the relatively low efficiency of the collection and treatment process of most discarded products.

For Mcdonald et al. (2016), these critiques do not call into question the principles of the circular economy but show to what extent it is necessary to carry out an indepth reflection on this concept while taking these limits into account. This involves, among other things, questioning the modalities of our economic growth and finding a consensus on the best strategy to adopt between “efficiency and sufficiency” to limit the consumption of resources and CO_2 emissions (Figge et al., 2014). For supporters of ecological economics, economic development must take into account planetary limits. This is the principle of “strong” sustainability. In this context, the environment must be considered as the support of all human activity in which the input data is the capacity of the environment to provide resources and absorb waste, and the output (resulting) the level development (Boutaud et al., 2006). The circular economy, placed in this context of sustainable growth therefore takes on its full meaning.

4 Conclusions

The COVID-19 crisis has had many negative repercussions on the socio-economic functioning of our economies. Despite the WHO alerts and the obvious health emergency, public authorities have been slow to implement strict health measures to limit the spread of the virus. At the same time, numerous IPCC reports warning of the consequences of our human activities on the planet (IPCC, 2018) have not prevented the current rise in CO_2 emissions. Meyer and Kunreuther (2017) recognize that this rather paradoxical behavior is attributable to cognitive biases which lead individuals to be “ostriches” in other words, to deny obvious risky situations. The myopia bias, which assumes that individuals favor urgent short-term risks over long-term investment, is a perfect example of this paradox. This bias explains the low level of investment in climate change adaptation and mitigation measures. The effects of climate change are perceived in the longer term and therefore less urgent.

However, it should be recognized that the exceptional economic and health measures put in place by governments to limit the spread of the COVID-19 virus and stimulate economies are all examples that show that large-scale and collective action is possible to fight against global warming. Nearly \$8.4 trillion has been released by governments in just 10 weeks to stem the spread of the virus.

Likewise, the shutdown of industrial activities that are sources of pollution, the refocusing of activities around essential needs, the local economy, etc., are all changes in our consumption and production patterns that have shown us that more sustainable economic development is possible. However, the positive impacts on the climate (Achebak et al., 2021; ESA, 2021; IEA, 2020) were only temporary. In China, for example, satellite observations from NASA (2020c) show that 3 months after the confinement period of February 2020, the level of nitrogen dioxide pollution experienced a return to “normal” during this period of 1 year. For Le Quéré et al. (2020) these rebound effects can be explained by the fact that the changes induced by the health measures linked to COVID-19 do not reflect the structural changes in global economies.

So in order to effectively fight against global warming, the post-COVID-19 world economies must move away from the traditional and linear logic of economic development aimed at “producing, consuming and throwing away” to move toward an economic development, which tends to limit the waste of resources and environmental impact, while increasing efficiency at all stages of product economics. This is the principle of the circular economy. However, the latter will only be effective in combating global warming and preserving the environment if it takes into account planetary limits.

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COVID-19's Impact on Eliminating Fossil Fuel Subsidies, Hence Fuel Poverty and Energy Justice

Robin Dickinson

Abbreviations

FFS	Fossil fuel subsidy
GDP	Gross domestic product
GHG	Greenhouse gas
G20	The Group of 20
IEA	International Energy Agency
IISD	International Institute for Sustainable Development
IMF	International Monetary Fund
OECD	Organisation for Economic Co-operation and Development
OPEC	Organisation of Petroleum Exporting Countries
SDG	Sustainable Development Goal
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WB	The World Bank
WTO	World Trade Organization

1 Introduction

On 5 June 2020, Dr. Fatih Birol, Executive Director of the International Energy Agency (IEA), quoted as follows in an Organisation for Economic Cooperation and Development (OECD) press release: "Fossil fuel subsidies are a roadblock to

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achieving a sustainable recovery from the Covid-19 crisis . . . Today's low fossil fuel prices offer countries a golden opportunity to phase out consumption subsidies. As governments look to boost jobs and plan for a better and more resilient future, it is essential to avoid market distortions that favour polluting and inefficient technologies" (OECD, 2020a). Unpicking the context of this statement and dissecting future impacts on fuel poverty, energy access and the fairness and justice of energy distribution will be the focus of this chapter.

We will explore why reform of fossil fuel subsidy (FFS) evolved into a mainstream global political objective over the last decade and include a discussion of the pragmatic quantitative definitions of FFS that underpin the critique of FFS reform. We will discuss the potential for FFS reform to impact energy poverty and why energy access is the more appropriate concept to use in this context, along with how energy justice is a new lens through which to view the FFS reform challenge. A review of the environmental climate gains still possible from FFS removal and why the territorial focus should be reduced to just 25 countries follows next. This leads on to a discussion of the policy challenges and the advances in policy instruments that could aid the replacement of FFS. Finally, we will explore the regressive impact COVID-19 has had on energy justice and the progress of reforming FFS but equally the platform national COVID-19 recovery plans provide for a rapid and complete resolution to the issues generated by FFS in high FFS territories.

2 How the Issue of Fossil Fuel Subsidy Removal Has Become a Global Political Mainstream Issue

The Group of 20 (G20) is the international forum that brings together the world's major economies. Its members account for more than 80% of world GDP, 75% of global trade and 60% of the population of the planet (The G20, 2021). The forum has met every year since 1999 and includes, since 2008, a yearly summit, with the participation of the respective Heads of State and Government (The G20, 2021). The resulting post summit communiques represent a unified perspective of the future policy directions of these countries. In this context, it was instructive that the communique of just the third summit in Pittsburgh 2009 (G20, 2009) made the following reference: 'The Organization for Economic Cooperation and Development (OECD) and the International Energy Agency (IEA) have found that eliminating fossil fuel subsidies by 2020 would reduce global greenhouse gas emissions in 2050 by ten percent. Many countries are reducing fossil fuel subsidies while preventing adverse impact on the poorest'.

The OECD and IEA were not the only actors, at that time, reviewing a growing body of analysis and case studies and, in conclusion, promoting the benefits and mechanisms of FFS removal. In late 2009, the Global Subsidies Initiative of the International Institute of Sustainable Development (IISD), based in Geneva, published a substantive report on the 'Politics of fossil fuel subsidies'. It observed that 'Reforming—ideally eliminating—such subsidies is a widely discussed "no-lose" (or "win-win") policy that could improve energy security, protect the environment and also promote economic growth' of developed and developing countries (Victor, 2009). Additionally, in early 2010, a small number of non-G20 countries came together as the 'Friends of Fossil Fuel Subsidy Reform', a group which has subsequently grown to number 30 countries and 50 sustainable development focused NGOs and for-profit organizations (FFFSR, 2021).

In Pittsburgh, the FFS reform proposition seemed to resonate across the G20, and the final communique went on to establish a plan of action to phase out FFS:

Extract from the G20 Communique Pittsburgh 2009

29. Enhancing our energy efficiency can play an important, positive role in promoting energy security and fighting climate change. Inefficient fossil fuel subsidies encourage wasteful consumption, distort markets, impede investment in clean energy sources and undermine efforts to deal with climate change. The Organization for Economic Cooperation and Development (OECD) and the IEA have found that eliminating fossil fuel subsidies by 2020 would reduce global greenhouse gas emissions in 2050 by ten percent. Many countries are reducing fossil fuel subsidies while preventing adverse impact on the poorest. Building on these efforts and recognizing the challenges of populations suffering from energy poverty, we commit to:

Rationalize and phase out over the medium term inefficient fossil fuel subsidies that encourage wasteful consumption. As we do that, we recognize the importance of providing those in need with essential energy services, including through the use of targeted cash transfers and other appropriate mechanisms. This reform will not apply to our support for clean energy, renewables, and technologies that dramatically reduce greenhouse gas emissions. We will have our Energy and Finance Ministers, based on their national circumstances, develop implementation strategies and timeframes, and report back to Leaders at the next Summit. We ask the international financial institutions to offer support to countries in this process. We call on all nations to adopt policies that will phase out such subsidies worldwide (G20, 2009).

This commitment to FFS reform went on to be reaffirmed at almost every G20 summit over the following decade with the G20 communiques from the Riyad summit, November 2020, stating "31. ... We reaffirm our joint commitment on medium term rationalization and phasing-out of inefficient fossil fuel subsidies that encourage wasteful consumption, while providing targeted support for the poorest" (G20, 2020).

3 What Are Fossil Fuel Subsidies?

Before we can assess the impact of FFS removal, we need to define a pragmatic scope for FFS that would allow for their identification and assessment. The G20 similarly identified this challenge in Pittsburgh, 2009: '30. We request relevant

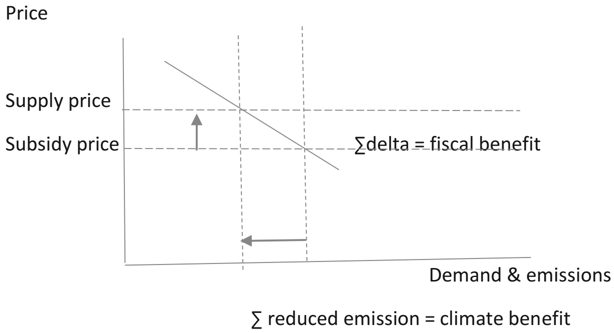


Fig. 1 The benefits of the ‘Price Gap’ method, by the author

institutions, such as the IEA, OPEC, OECD, and World Bank, provide an analysis of the scope of energy subsidies … and suggestions for the implementation of this initiative and report back at the next summit’ (G20, 2009).

The resulting 200-page report (IEA, OPEC, OECD, World Bank, 2010) was produced for the G20 by a group of leading multinational research and policy institutions. It was so comprehensive in its scope that it has been taken as the baseline analysis for the development of the discussions surrounding FFS reform within this chapter.

In terms of scoping the FFS removal challenge, the 2010 report to the G20 (IEA, OPEC, OECD, World Bank, 2010) determined that FFS impact should be assessed largely in two dimensions: fiscal dollars and climate impact; while having regard to a third dimension—impact on the poorest—and a fourth dimension—‘efficiency’. The simple quantitative methodology that was adopted to underpin this assessment was the so-called Price Gap method. This metric tracks the direct (pre-tax) consumer subsidies of fossil fuels (oil, gas, coal). By this measure, FFS removal provides a fiscal surplus to governments and a corresponding CO_2 emissions benefit for humanity (and for governments with regard to their future emissions reduction targets) arising from the reduced consumption of fossil fuels. These benefits are illustrated in the model in Fig. 1.

The simplicity of the ‘Price Gap’ method has led to its widespread use in modelling future FFS removal scenarios (for example Kosmo, 1988; Larsen & Shah, 1992; Coady et al., 2010). The IEA also uses the ‘Price Gap’ method and has created a corresponding annual time series database of FFS that is dimensioned by country and fuel type and is openly available (IEA, 2021).

However, the simplicity of the ‘Price Gap’ method has its limitations in supporting FFS assessments as noted in the original 2010 report to the G20 (IEA, OPEC, OECD, World Bank, 2010), see box below.

Challenges and Limitations of the Price-Gap Methodology

This report relies on estimations of market price differentials, or price-gaps, for various sources of energy. It should be recognized that this method relies on a number of assumptions:

1. Identifying the appropriate cost. Many different measures of cost exist, including average cost, marginal cost and opportunity cost. Exporting countries with large energy endowments prefer to use cost of production as a benchmark. What is more, energy costs are highly variable as not all commodities are widely traded.
2. Identifying the appropriate price. Although the price quoted in global markets is typically used as a measure of opportunity cost, international prices may be distorted by a variety of factors and can experience a high degree of volatility.
3. Price-gap estimates do not capture producer subsidies. Therefore, subsidy estimates based only on price-gap measurements tend to underestimate the level of subsidies in developed countries.

Other caveats also necessitate exercising caution when interpreting or explaining market transfers (to consumers) and market price support (to producers) in any given year. In international markets, U.S. dollar prices, especially of crude oil and petroleum products, have been highly volatile in recent decades, as has the value of the U.S. dollar against other currencies. These two elements combine to make estimates of market transfers from 1 year to the next also highly variable. (IEA, OPEC, OECD, World Bank, 2010).

Additionally, and significantly, the 'Price Gap' method barely addresses the common definition of a 'subsidy' that the vast majority of countries have agreed with the World Trade Organisation (WTO): 'a "subsidy" exists when there is a "financial contribution" by a government or public body that confers a "benefit"' (WTO, 1994). For the full WTO definition of a subsidy, see the box below.

WTO Definition of a Subsidy

'Article 1 of the WTO Agreement on Subsidies and Countervailing Measures (ACMS) (WTO, 1994) states that a "subsidy" exists when there is a "financial contribution" by a government or public body that confers a "benefit". A "financial contribution" arises where: (i) a government practice involves a direct transfer of funds (e.g. grants, loans, and equity infusion), potential direct transfers of funds or liabilities (e.g. loan guarantees); (ii) government revenue that is otherwise due is foregone or not collected (e.g. fiscal incentives such as tax credits); (iii) a government provides goods or services other than general infrastructure, or purchases goods; or (iv) a government entrusts or directs a private body to carry out one or more of the above functions. A "benefit" is conferred when the "financial contribution" is provided to the recipient on terms that are more favorable than those that the recipient could have obtained from the market' (WTO, 1994).

However, as noted in the 2010 paper (IEA, OPEC, OECD, World Bank, 2010), broader subsidy information is not always available at a country level, and indirect subsidies are hard to estimate, let alone estimate consistently across countries.

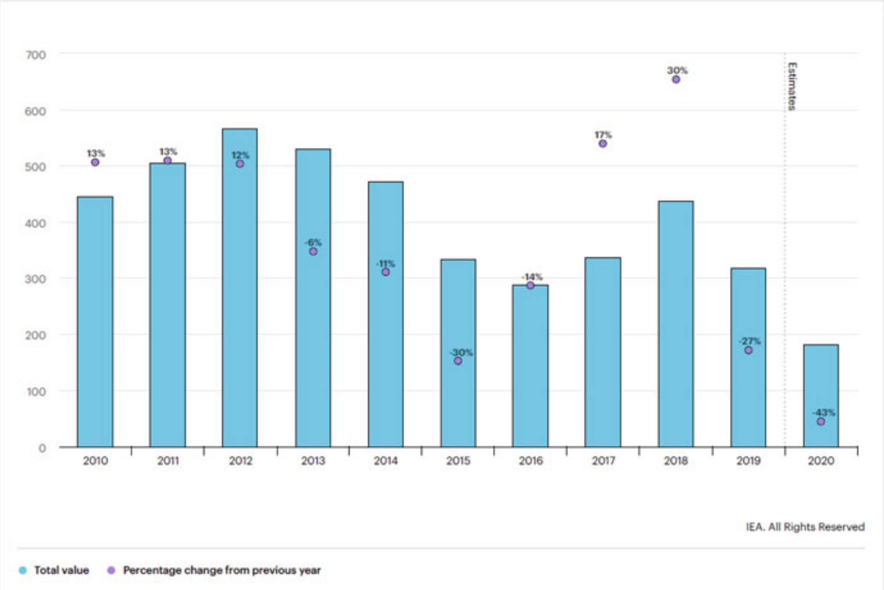


Fig. 2 Value of fossil fuel consumption subsidies, 2010–2020 (IEA, 2020e)

Notwithstanding these challenges, in the decade since 2010 there have been progressive attempts to extend the scope of the FFS assessment methods from 'Price Gap' towards addressing the full WTO definition. It is worth understanding the effect these revised methods have on the estimated fiscal values associated with FFS. Specifically, the scale of fiscal underestimation arising from use of the simpler 'Price Gap' method. As a baseline, Fig. 2 indicates the value of annual global consumption-based FFS as determined by the IEA using the 'Price Gap' method over the period 2010–2020.

The period 2017–2019 are the last 3 years for which complete FFS data is available and the economies of the G20 publish a rich variety of underlying economic data that makes the calculation of FFS robust. Within this context the IEA estimation for consumption FFS (averaged over the 3 years 2017–2019 calculated by author from IEA, 2020e), amounts to $104 billion per annum.

For their FFS calculations, the OECD extend the 'Price Gap' method by additionally including the subsidy (including direct budgetary transfers and tax concessions) of fossil fuel production. Thus, according to the OECD (2021), the total annual FFS for the G20 economies, averaged over 2017–2019, would be $223bn p.a. or 115% higher than that derived by the IEA. (N.B. Interrogating their database, it is clear that the OECD method also includes the indirect subsidy of fossil fuel-generated electricity, which amounted to $11bn p.a. within the aforementioned figure (OECD, 2021)).

The Global Subsidy Initiative of the IISD have recently sought to estimate the fossil fuel subsidy of the G20 countries averaged over the period 2017–2019 with a method that is as near as possible to the WTO subsidy definition (IISD, ODI, OCI, 2020a). It takes account of:

1. 'Direct budget transfers and tax expenditures.
2. Price support (induced transfers) through regulated below-market prices for consumers.
3. Public finance (e.g., loans and guarantees) at both market and below-market value.
4. State-owned enterprise (SOE) investment (e.g., capital expenditure for projects via equity or debt) at both market and below-market value.'

Though the IISD do observe that the method by which they account for public finance and state-owned enterprise investment (3 and 4 above) could go beyond the scope of the WTO subsidy definition (IISD, ODI, OCI, 2020a). The overall FFS figure they model is $584 billion annually for the G20 countries averaged over the 3 years 2017–2019, some 460% higher than the IEA 'Price Gap'-based estimate of $104 billion (IISD, ODI, OCI, 2020b).

At this point, it is also worth noting that Coady et al. (2015, 2019), in their IMF working papers, seek to extend the scope of FFS on economic grounds into what they deem to be the 'Post-tax' realm. They do this by accounting for the fiscal impact of social and environmental externalities, such things as the impact of fossil fuel pollution on national health services. They come up with fiscal numbers associated with FFS that are an order of magnitude higher than those produced by the 'Price Gap' method. They take a global scope not limited to the G20. Taking their method, for the year 2017, they calculate the value of global FFS to be $5200bn as compared to the IEA estimate for global FFS in 2017 of $340bn (IEA, 2020a). Coady et al.'s estimate being some 1430% higher. A more detailed exploration of the differences in estimations and methods between Coady et al., and the IEA is available in a critical examination by Skovgaard (2017).

What is clear is that though it is simple and measurable, the 'Price Gap' method significantly underestimates the fiscal impacts of FFS and the potential fiscal benefits accruing to countries arising from their removal. Though the lower IEA 2017 global FFS figure of $340bn is still significant.

Finally, before we explore the connection between FFS and Fuel Poverty in the next section, it is worth noting that FFS are very fiscally inefficient and regressive policies for providing social support. The Independent Evaluation Group of WB undertook a review in 2008 (IEG, 2008) and concluded that on average, the lower 40% of income earners in a country receive only 15–20% of the fiscal support provided through FFS. This finding backed up an earlier IMF study (Coady et al., 2006) which had a slightly wider range of 15–25% of fiscal support being received the lowest-earning 40% of a population. The argument supporting the use of FFS is that, at that time, there may not have been any pragmatic alternatives to provide welfare support to the lowest-earning 40% in those countries.

4 The Impact of Fossil Fuel Subsidies on Fuel Poverty, Energy Access and Energy Justice

Unlike FFS which is essentially quantitative in nature, Fuel Poverty and Energy Justice are much more qualitative concepts. As such they depend upon the societal (country) context to which they are applied. In the previous section, we focused the assessment of FFS on those countries where FFS are applied on a direct, pre-tax, consumption basis for oil, gas and coal. It is these countries (see Fig. 4 for a list) that will also be focus of this section, for a discussion of Fuel Poverty and Energy Justice.

There are many variants to the definition of Fuel Poverty. One example is that used within the United Kingdom. It was provided within the UK Government's 2012 Fuel Poverty review conducted by John Hills (2012) and has two components. The definition states Households are in Fuel Poverty when: 'They have required fuel costs that are above the median level; and where they to spend that amount, they would be left with a residual income below the official poverty line'. When we examine the list of countries who still provide substantial consumption FFS (see Fig. 4), it is apparent that it does not include the leading industrialized nations, and it would be these nations where concepts such as residual (including welfare) income can be considered to have universal applicability. In fact, the FFS list is predominantly one of developing countries outside the G20 where definitions of absolute poverty are material considerations when describing the population quartile with the lowest income. In this context, it maybe more pertinent to consider the term Energy Access as the principal challenge for the poorest quartile of these populations and not Fuel Poverty.

The IEA define Energy Access as '*a household having reliable and affordable access to both clean cooking facilities and to electricity, which is enough to supply a basic bundle of energy services initially, and then an increasing level of electricity over time to reach the regional average*' (IEA, 2020b), and they use this as a metric in their analysis and projections.

It should also be noted that currently the largest and most resourced initiative to address the issues of those living in absolute poverty around the world is the 2030 UN Agenda for Sustainable Development signed by all the states of the United Nations in 2015. The term 'Energy Access' is included within the agenda and is the basis of Sustainable Development Goal (SDG) 7. 'Ensure access to affordable, reliable, sustainable and modern energy for all' with an associated target 7.1 being 'By 2030, ensure universal access to affordable, reliable and modern energy services' (United Nations, 2021a).

While Energy Access provides foundations for quantifiable metrics, the term 'Energy Justice' is an evolving qualitative concept and the subject of a growing body of research, as can be evidenced by a query to Google Scholar on 27 February 2021 which returned 3840 entries referencing the term since 2017. Simply put 'Energy Justice' looks at the justice of energy access and energy development decisions as opposed to reviewing these decisions through economic or environmental lenses.

Energy Justice is based upon the principles of the established field of 'Social Justice'. However, contemporarily, the focus of 'Energy Justice' tends to be concerned with the individual household experience as opposed to the National Collective. Clearly Energy Justice represents a huge scope to review, so in this section, we will seek only to use the lens of Energy Justice to reflect on the issues of Energy Access for households in our target countries with consumption FFS.

A baseline review of FFS removal from the perspective of Energy Access and Energy Justice can start with the 2010 report to the G20 (OECD, IEA, WB, OPEC, 2010) that observed that access to energy is critical to reducing poverty and increasing economic development. It references the IEA observation that energy 'is a vital input to all sectors of the economy, fuelling transport to move goods and people and providing electricity to industry, commerce, agriculture, and important social services such as education and health. Energy is an essential catalyst for economic growth and improving standards of living, yet access to modern energy services remains an elusive goal for the 1.5 billion people that lack access to electricity services' and that '2.5 billion people used traditional biomass for cooking and heating and there was huge desire for energy to support private transportation' (IEA, 2009). They also referenced a WB observation that FFS did actually provide benefits to the poorest strata of society within developing countries 'Low-income groups spend a higher proportion of their energy budget on cooking fuels and less on electricity and private transportation. Where subsidies result in switching from traditional fuels and improved access to electricity, such subsidies can bring considerable benefits to the poor. These include less indoor pollution, and less time spent collecting fuel wood, so more time for productive activities. In most cases there are significant differences between the consumption patterns of the rural and urban poor. Subsidies for diesel and gasoline are particularly regressive, as these fuels are used primarily for private transport. Subsidies for kerosene and LPG are potentially less regressive or even neutral, as these fuels are used by the poor for cooking, and for lighting in rural areas' (World Bank, 2008). To demonstrate the above observation, the WB reference an FFS example from Senegal where introducing an FFS 'resulted in a shift away from charcoal consumption, with nearly 85% of households in the capital, Dakar, and 66% of households in other urban areas now owning LPG stoves' (UNEP, 2004).

For the reasons highlighted above, there should be significant concerns, from an Energy Justice perspective, as to process and policy frameworks surrounding FFS removal and its impact on the poorest households within the developing countries concerned. Early case studies referenced in the 2010 report to the G20 (OECD, IEA, WB, OPEC, 2010) highlighted the challenge: FFS removal of Fuel, Kerosene, Gas and LPG in Egypt reduced the income of the bottom quintile of the population by 7.7% (Abouleinein et al., 2009) and FFS removal of petrol, kerosene and LPG in Ghana reduced the income of the bottom quintile of the population by 9.1% (Coady et al., 2006). However, it should be noted that the most up to date modelling (as explored in Sect. 5) indicates that FFS removal has a positive impact on household real disposable incomes for the poorest quartile across all scenarios, in all of the remaining higher FFS countries, by 2030 (Chepeliev & Van der Mensbrugghe, 2020).

Since 2010, effectively managed FFS reform has been seen as a progressive global policy by the United Nations. After a substantial international consultation, it was included within the UN 2030 Agenda for Sustainable Development (United Nations, 2021c) as a part of SDG 12 'Ensure sustainable consumption and production Patterns' specifically Target 12.c (see the box below).

FFS Reform Targets of SDG 12

'Target 12.c Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities.

Indicator 12.c.1 Amount of fossil fuel subsidies per unit of GDP (production and consumption) and as a proportion of total national expenditure on fossil fuels' (United Nations, 2021b).

Since 2015, the UN has gone on to connect FFS reform with other SDGs: SDG 1 'No Poverty' noting FFS reforms combined with targeted social welfare can address poverty; SDG 3 'Health and Wellbeing' noting FFS reforms and taxing fossil fuels could reduce global air pollution; SDG 7 'Affordable and Clean Energy' noting FFS can inhibit the take up of new low carbon technologies (UNEP, OECD, IISD, 2019).

As we have discussed previously, FFS reform not only has large Fiscal and Social impacts, it also has globally significant climate impacts through generating a corresponding reduction in GHG emissions. In this way, FFS reform is connected to SDG 13 'Climate Action'. The scale of the possible reduction in GHG emissions is explored in the next section.

5 How Removing Fossil Fuel Subsidy Could Aid Country Efforts to Address Climate Change

The United Nations Framework Convention on Climate Change (UNFCCC) was ratified in 1994 to seek to identify and mitigate the changes associated with anthropologically induced climate change. After many attempts, in December 2015, 196 countries signed a legally binding agreement to limit global warming to well below 2 °C, preferably to 1.5 °C, compared to pre-industrial levels. This has become known as the Paris Agreement. Within the agreement there is a requirement on countries, by 2020, to publish plans known as nationally determined contributions (NDCs) on how they are going to achieve their contribution to limit global warming (UNFCCC, 2021a, b) .

Naturally, much work has been undertaken since the 2015 Paris Agreement to estimate the impact of the removal of FFS on the national targets set by the agreement. However, global estimates for the GHG gains to be made from FFS removal were already being prepared within the report to the G20 in 2010 (OECD, IEA, WB, OPEC, 2010). Using IEA 'Price-gap' data (IEA, 2008) and extending an economic model developed by the OECD (2009), the conclusion was that removal of all consumption FFS by 2020 would generate a 10% reduction in global GHG emissions by 2050.

The foundation GHG reduction estimate published in 2010 has been further refined in the intervening years, using a variety of different economic models based upon revisions of 'Price Gap' data and other economic models. For example, in 2014 Schwanitz et al. (2014) estimated, by applying data to a different economic model, that consumption FFS removal would result in a 5.3% reduction in global GHG emissions by 2035 rising to a 6.4% reduction by 2050 (a lower reduction than the 2010 estimate). By 2018, Jewell and her colleagues had applied 'Price Gap' estimations for FFS removal to five different economic models that additionally took account of the potential for low or high future fossil fuel price scenarios (Jewell et al 2018). The results showed a degree of alignment across the different models used and estimated global GHG emissions reductions in 2030, even with low future fuel prices, in the range of 1–4%, continuing to a tighter 3–4% range for the GHG emissions reduction in 2050. Again, this is less of reduction than the previously described estimates in 2010 and 2014, lowering the potential impact of FFS removal.

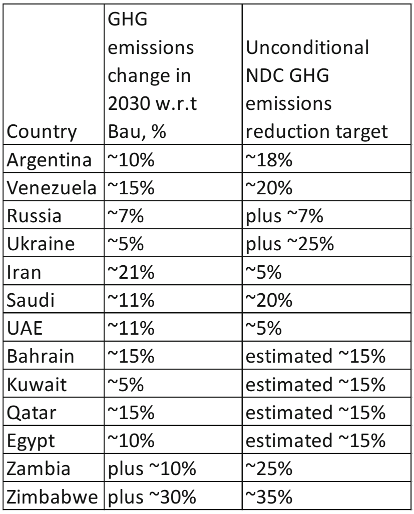
The most recent modelling for GHG reduction arising from FFS reform by Chepeliev and Van der Mensbrugghe (2020) using a different economic model with 'Price Gap' data but one that allowed for greater precision within the findings that supported a disaggregated analysis of FFS by fuel type and supported GHG emission reduction projections down to national levels in the 25 countries who still operated substantial consumption-based FFS. The modelling estimated that global GHG emission reductions of 1.8–3.2% were still attainable globally by 2030 (tighter than the 1–4% range estimated by Jewell et al. in 2018). Importantly, for the 25 high subsidy countries, the model predicted they would all meet more than 50% of their 2030 NDC targets under the 2015 Paris Agreement, with many countries, with the exceptions of Zambia and Zimbabwe, exceeding them (see Fig. 3 for a data extract). This provides an added incentive to accelerate FFS reform in these countries.

Having also established the global material benefits of FFS reform on the mitigation of climate change, the next section will explore some of the pragmatic challenges associated with implementing FFS reform within the countries where FFS are still applied.

6 Overcoming the Challenges of Fossil Fuel Subsidy Removal

Back in 2009 Victor writing for the Global Subsidy Initiative of IISD (Victor, 2009) proposed that the principal challenges associated with FFS removal were those

Fig. 3 Data extract from results of Chepeliev and van der Mensbrugghe modelling of country level FFS reform (Chepeliev & Van der Mensbrugghe, 2020)



Country	GHG emissions change in 2030 w.r.t Bau, %	Unconditional NDC GHG emissions reduction target
Argentina	~10%	~18%
Venezuela	~15%	~20%
Russia	~7%	plus ~7%
Ukraine	~5%	plus ~25%
Iran	~21%	~5%
Saudi	~11%	~20%
UAE	~11%	~5%
Bahrain	~15%	estimated ~15%
Kuwait	~5%	estimated ~15%
Qatar	~15%	estimated ~15%
Egypt	~10%	estimated ~15%
Zambia	plus ~10%	~25%
Zimbabwe	plus ~30%	~35%

of Political Economy. Thus, FFS arose principally from well-organized interest groups who remain active, and the politicians who see advantage in being seen to provide a ‘costly’ service to favour these groups. The flip side is that FFS are relatively easy to administer, and there may not be the capability within the country to deliver alternative levels of support to interest groups nor the poor. Interestingly, FFS occur in many authoritarian regimes who fear instability and where FFS could be perceived as visible carrots for the populous.

Concerning the removal of FFS, the Political Economy viewpoint has provided an excellent perspective on why FFS reform has been successful when implemented. This has been supported by the many case studies that have been published in the intervening years, for example by Inchauste and Victor (2017).

If overcoming the overtly political challenges of achieving FFS reform are put to one side, a principle challenge for FFS reform, from what would be described now as an Energy Access and Energy Justice perspective, is how to target the poor in developing countries with alternative methods of financial support. The 2010 report to the G20 (IEA, OPEC, OECD, World Bank, 2010) outlined a number of options:

- Replacing FFS with direct cash payments (otherwise known as a Safety net) maybe problematic to deliver quickly and not be universally accessible by households in developing countries. They may also be problematic from an administrative perspective as well.
- Vouchers or smart cards may offer alternative payment mechanisms but bring their own administrative burdens.
- More fruitful could be Near Cash Transfers, such as waiving fees for services such as health, education or transportation which may work more effectively.

- In rural areas where FFS alternatives are limited, better targeting of the poorest maybe available through the focussing of subsidies on products (other than energy) that only the poor use.
- However, as a last resort, if nothing else can be done, LPG and kerosene are fossil fuels most useful to the rural poor for cooking and heating. Reducing demand for these two fuels through FFS removal would be likely to only have small fiscal and GHG impact compared to FFS removal on gasoline, diesel, coal or natural gas and so LPG- and kerosene-specific FFS could be allowed to persist.

In 2011 the World Bank (WB), OPEC and OECD (IEA, OPEC, OECD, World Bank, 2011) reviewed a large number of previously published case studies and found that three strategies had some positive effect in supporting, what we would now consider to be Energy Access and Energy Justice for the economically poorest households who were experiencing FFS removal within a developing country. In summary these three strategies were: strengthening safety nets; informing the public along with providing one off compensation measures; including FFS removal as part of a broader reform of the energy sector.

In the intervening years, since the original report to the G20 in 2010, it has been recognized that from an administrative and enabling infrastructure perspective, delivering new support programmes that would act as substitutes for FFS was not a trivial task for governments to deliver. Therefore, technical intergovernmental advisory support was needed to build the required infrastructure capacity.

A consortium ESMAP (2021) led by the World Bank (WB) has taken a considerable lead in providing technical assistance to developing countries on effective FFS removal programmes. In 2013, they set up the Energy Subsidy Reform Technical Assistance Facility (ESRAF) with a budget to help countries remove fossil fuel subsidies while protecting the poor. By 2017 the ESRAF had published an open series of guidance notes to facilitate local country policy development on approaches to FFS removal, along with numerous case studies (Flochel & Gooptu, 2018). In their latest annual report (ESMAP, 2020), the ESMAP consortium record the substantial number of engagements they have undertaken in the period since 2017, working with many of the 25 countries still operating consumer FFS to implement reforming policies and programmes.

The effect of the latest efforts for FFS reform in the context of improving Energy Access within a country while taking account of Energy Justice is illustrated in country case studies that published by UNEP OECD and IISD in 2019 (UNEP, OECD, IISD, 2019). One example is replicated in the box below.

Morocco: Freeing Up 6.6% of GDP to Finance Education, Health, Poverty Reduction and Renewable Energy

'Morocco combined extensive reforms of its fossil fuel subsidies with investments in social protection programmes, education and health. The reforms increased fiscal space and allowed investments in strategic areas such as renewable energy while mitigating impacts on the poor. Due to the balanced approach to distributional, welfare, poverty, and government budget perspectives, Verme and El-Massnaoui

(2017) qualified them as “perhaps the most rational reforms undertaken in the Middle East and North Africa region in recent years”. A subsidy system for petroleum products and other commodities had been in place in Morocco since the 1940s. Morocco has no developed domestic resources of fossil fuels. The provision of fuels at a fixed price led to subsidies dependent on world market prices and led to high costs for subsidies in times of high global fuel prices. In 2012, as a result of high world market prices for fossil fuels, expenditures for subsidies reached 6.6 per cent of GDP.

The government reacted by reinstalling a previous price indexation mechanism, combined with a cap on unit subsidies for gasoline, diesel, and fuel oil. These measures, combined with a decline in international oil prices, resulted in a reduction of the value of subsidies by 24 per cent (or almost 2 per cent of GDP) in 2013. In 2014, the government stopped subsidizing the prices of gasoline and industrial fuel oil, and started phasing out subsidies to diesel. This resulted in further budgetary savings of almost 20 per cent (or 1 per cent of GDP). By end-2015, prices of all petroleum products were fully liberalized and total spending on subsidies fell to 1.1 per cent of GDP in early 2016 (Verme & El-Massnaoui, 2017). The Government of Morocco chose to make the subsidy reforms socially equitable and “pro-poor”. The reforms abolished the most regressive subsidies, namely on gasoline, diesel and fuel oil, which disproportionately benefited the wealthier strata of the population. Subsidies on liquefied petroleum gas (LPG), which benefit mostly the poorer segments, were retained. Support to the national electricity company was largely reduced by removing subsidies for fuel oil used to generate electricity. The effect of rising electricity prices on poor consumers was mitigated by redefining the consumption brackets and freezing tariffs for those in the lowest consumption brackets. Verme and El-Massnaoui (2017) estimate that the welfare effects of reforms were mostly felt by higher-income households. At the same time, the government invested heavily to expand social cash transfer schemes and health insurance for the poor. The 2015 budget foresaw a considerable increase in spending on education, an extension of the health-care programme, and a targeted cash transfer programme to fight against school drop-outs (Government of Morocco, 2015). The Tayssir Conditional Cash Transfer programme targeting poor rural households was expanded from 80,000 families in 2009 to 466,000 families in 2014. Similarly, a health insurance scheme for the poor, Regime d’Assistance Medicale (RAMED), increased its coverage from 5.1 million beneficiaries in mid-2013 to 8.4 million beneficiaries in early 2015 (Merrill et al., 2016).’ (UNEP, OECD, IISD, 2019).

Having reviewed the possibilities and capacity available to countries to deliver FFS reform, in the next section we will explore additional possibilities for FFS arising from the COVID-19 pandemic.

7 COVID-19, an Opportunity to Refocus Country Efforts on Energy Access and Energy Justice Through the Removal of Fossil Fuel Subsidies

At the end of 2019, the IEA (2020a) reported the value of global FFS for the year as $202 bn, excluding electricity subsidies. Though less than half the $450 bn estimated for 2010, it still represents a substantial sum. Figure 4 illustrates the breakdown of FFS for the top 25 countries operating consumer FFS including fossil fuel-generated electricity in 2019.

The COVID-19 pandemic was declared in Q1 2020, and it has fundamentally changed the welfare and fiscal position of all countries across the world. The WB analysis in November 2020 (World Bank, 2020), based on the review of multiple growth forecasts modelled by the WB and IMF, has estimated that the number of people plunged into absolute poverty (living on between 1 and 5 US dollars a day), around the world, has increased by around 180 million people. This is a level last seen in 2015 and reverses a decade of decline. The analysis was regional showing the largest increases in South Asia (110 million) and sub-Saharan Africa (50 million which represented an increase of 33%). However, no region of the world was immune from increasing levels of absolute poverty (Lakner et al., 2021). Unsurprisingly, there has also been a reversal in improvements in Energy Access among the world's poorest. For example, predictions are that, even if they were

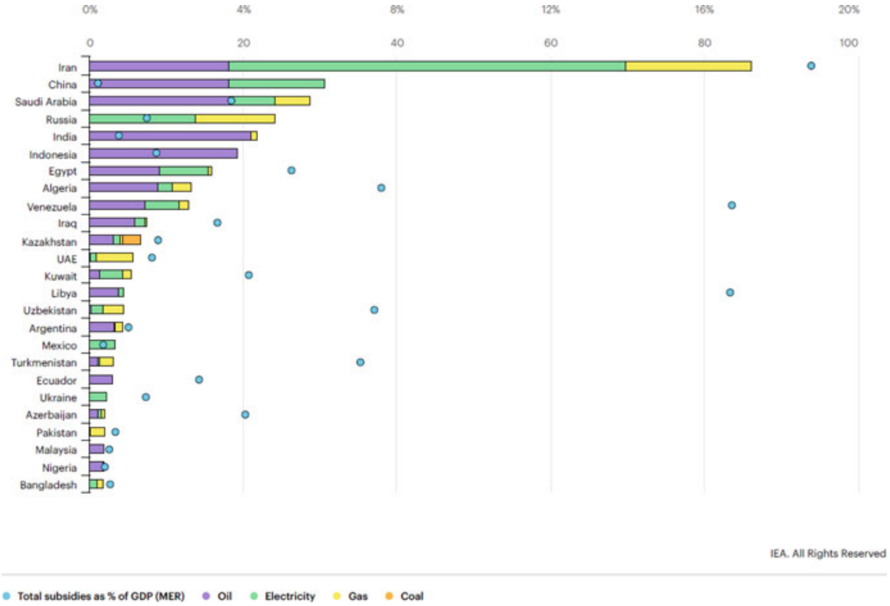


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Fig. 4 Value of fossil-fuel subsidies by fuel in the top 25 countries, 2019 (IEA, 2019)

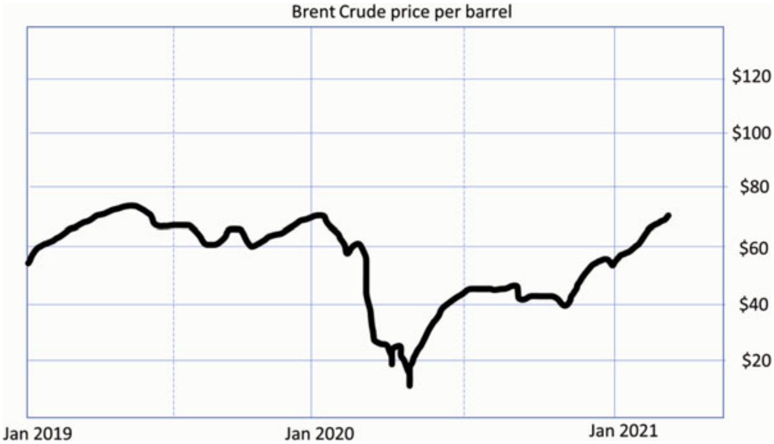

Fig. 5 Brent crude oil price chart 2019 to Q1 2021. (By the author)

connected to an electricity supply, 100 million people in sub-Saharan Africa will no longer be able to afford electricity, with many having to revert to more polluting forms of energy (IEA, 2020c). In the context of FFS, however, it can be noted from the countries listed in Fig. 4 that there is not a high correlation between countries still operating consumption FFS and countries in South Asia and sub-Saharan Africa.

Starting in June 2020, the IEA began leveraging the impact of the COVID-19 pandemic for FFS reform. It promoted rapid action on FFS reform particularly in producer countries where most of the significant consumption subsidies remain, by highlighting the possible fiscal and GHG reduction opportunity (this is where the chapter started with its opening quote (OECD, 2020a)). This IEA initiative followed a collapse in oil prices in April 2020 (see Fig. 5). The initiative was extended by the IEA with the publication of a more detailed reiteration of the FFS removal proposition and its application to the situation rendered by the global pandemic and governmental and fossil fuel market responses (IEA, 2020c).

However, the WB (ESMAP, 2020) took an alternative approach and viewed the FFS reform opportunity offered by the COVID-19 pandemic principally from an Energy Justice perspective. It did not recommend immediate action to resolve short-term fiscal stresses but proposed building FFS reform into the relevant countries post pandemic economic recovery plans, an approach supported by the subsequent apparent recovery in oil price to pre-pandemic levels. In fact, the ESMAP consortium led by the WB in their late 2020 annual report reflected on this issue specifically, see the box below.

Extract from ESMAP 2020 Annual Report on FFS Removal Post COVID-19

‘One of the tangential impacts of the COVID-19 pandemic was a major collapse in fossil fuel prices in early 2020. Typically, periods of low fossil fuel prices are when there is the greatest political opportunity for removing subsidies. However, the price collapse also coincided with an economic crisis that already reduced the ability of rate-payers to meet obligations, and removing state support in such a crisis is difficult. Subsidy removal, which disproportionately impacts the poor, also requires simultaneous compensation and mitigating support. ... Governments today can start introducing measures that prepare the country for future subsidy removal, like working on social safety nets. ESMAP and the World Bank have focused support on building more resilient and sensitive social safety nets to protect those hit by crisis now, while also creating a more conducive environment to subsidy removal in the future' (ESMAP, 2020).

The proposed strategy of focussing on the opportunities presented by post COVID-19 government recovery plans and stimulus packages to deliver enhanced FFS reform is also proposed by the OECD. They specifically warn against relaxing environmental regulations, propose building environmental improvements into new support mechanisms and suggest engaging in energy pricing restructuring including FFS removal (OECD, 2020b). It must be noted that the IEA (2020d) in their later update on responses to the COVID-19 pandemic do also promote the inclusion of FFS reform within country-level post COVID-19 recovery plans, suggesting a similar range of possible policy instruments to the OECD, with an additional focus on citizen communications.

To conclude, pursuing immediate opportunities for FFS reform in an era of fiscal limitation surrounding the COVID-19 pandemic, would most probably adversely impact the poorest households from an Energy Justice perspective, in a country where this occurs. However, the inevitability of country level build back strategies after COVID-19 do present an interesting opportunity for targeted enabling strategies that support and increase Energy Access for the poorest households and therefore would enable a new emphasis on FFS removal within those countries who still operate high consumer FFS.

A key milestone for assessing progress towards global GHG emission reductions, as was agreed between countries in the Paris Agreement (2015), is the UNFCCC conference of parties 26 (COP 26), which was delayed by the COVID-19 pandemic from November 2020. It will now be held in Glasgow, UK in November 2021. It offers a real opportunity for collaborative engagement to accelerate the enhancement of Energy Access and Energy Justice for the poorest citizens of the 25 countries who are still operating substantial consumer FFS. As has been highlighted earlier, if these 25 countries were to include well-mitigated FFS reform measures into their post COVID-19 recovery plans, it would also offer them potential relief to the fiscal stresses they have experienced, as well as making a substantial contribution to their 2030 global GHG emission reduction Nationally Determined Contribution (NDC) obligations.

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The Impact of the COVID Pandemic: What Can We Expect for Morocco's Energy Future?

Maryeme Kettani and María Eugenia Sanin

1 Introduction

At the writing time of this chapter, the world is experiencing a global pandemic produced by a virus known as COVID-19. Nearly all countries in the world have been hit by this pandemic that first started in China and then spread across the globe. To limit the diffusion of COVID-19 virus, many governments decided to put their population under lockdown. The authors aknowledge support from the Chair Energy & Prosperity.

The COVID-19 pandemic has caused a worldwide socio-economic crisis that can be seen at the same time as a demand crisis and as a supply crisis (International Energy Agency (IEA), (2020a, b); International Monetary Fund (IMF), 2020a). From the supply side, the shock comes from the deliberated shutdown of businesses considered non-essential such as restaurants, malls, hotels and even some factories. From the demand side, the shock comes mainly from the impact of lockdown on consumers' income and in a lesser sense on the change in consumption patterns. In several countries, unemployment has increased in an unprecedented manner. In Morocco, as in many developing countries, the most impacted are those in the lower income segments, who work in the informal economy which contributes to more than 20% of Moroccan GDP and employs millions of workers (Haut Comissariat au Plan (HCP), 2018; Confédération Générale des Entreprises du Maroc, 2014). As a result of the global fall in economic output, predictions state a worldwide annual GDP drop of around 2% for each month of containment measures (International Energy Agency (IEA), 2020a, b). Assuming that economic recovery is U-shaped and is accompanied by a substantial permanent loss on global

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GDP despite macroeconomic efforts, global GDP is expected to decline by 6% in 2020 (International Energy Agency (IEA), 2020a, b). GDP decline in each country will depend on many factors, including the magnitude and duration of national shutdowns, the extent of reduced demand for goods and services in different parts of the economy, and the speed at which significant fiscal and monetary policy support takes place.

The socio-economic impact of this unprecedented crisis would depend on two main factors: the duration of lockdowns and the shape of recovery. The latest will in turn be influenced by possible rebounds of the pandemic and affected by the macroeconomic policy responses set up by governments. Regardless of the efficiency of these policies to stimulate the economy, 2020 will be remembered as the year of the deepest post-war recession (International Energy Agency (IEA), 2020a, b), largely exceeding the impact of the 2008 financial crisis (International Monetary Fund (IMF), 2020b).

For oil importer MENA countries, average growth in 2020 is expected to contract in between 1 and 4.5% points below 2019s level (International Monetary Fund (IMF), 2020a). The decline in global demand for led to a drop in international commodity prices affecting food and oil-commodity exporters such as Morocco, Tunisia, Pakistan, and Jordan, with additional negative impacts on trade and tourism. The pandemic has also weakened demand for touristic activities. For Morocco, tourism is one of the main sources of foreign exchange and revenue. A challenging issue for oil importers relies on their dependence on imports to satisfy their domestic energy requirements. Generalized disruption in global trade, including energy primary sources, may put local utilities at financial risk, making it difficult to maintain domestic security of supply.

Regarding the power sector, electricity demand dropped sharply in several European countries due to the containment and closure of many economic sectors. According to the most recent publication of the International Energy Agency (2020a, b), and based on analysis of daily data through mid-April for 30 countries representing two thirds of global energy consumption in the world, countries in full lockdown experienced an average decline in energy demand of 25% per week and countries in partial lockdown average 18% decline per week. Global energy demand in the first quarter of 2020 (Q1 2020) declined by 3.8%, or 150 million tons of oil equivalent (Mtoe), relative to the first quarter of 2019. Electricity demand has decreased by 20% or more during periods of full lockdown in several countries. Regional impacts on Q1 2020 energy demand has been different between countries depending on the dates of lockdowns implementation as well as how lockdowns affected demand in each country. For example, in countries like Korea and Japan, with less stringent restrictions during 2020, the impact on energy demand was limited to below 10% on average. Even though electricity consumption from the residential sector has slightly increased due to a longer time spent at home and to teleworking, this small increase has been compensated by the drop in electricity demand caused by the shutdown of industries, shops, hotels, etc. The shape of the demand load also changed, looking more like the shape of a prolonged Sunday.

In Morocco, public authorities rapidly put in place a strategy to contain the spread of the virus by setting very restrictive measures to limit the risk of the virus propagation. The lockdown period in Morocco started on the 20th of March at 8 pm and was then extended until the 12th of June. Morocco is one of the latest countries to adopt a progressive exit of lockdown (phase 3 of progressive exit of lockdown started[1] as from the 13th of June 2020). However, even if the county adopted strict lockdown measures from March to June, and despite a progressive regional exit strategy, the number of cases has increased during the second semester of 2020. In Mid-July, the Norther region of Tanger (second in terms of GDP and source of major touristic revenue) started a new lockdown period.

2 Effect of the Pandemic on the Moroccan Economy in Comparison to World Trends

In this section, we underline the economic impacts of lockdown and the generalized global crisis on the Moroccan economy during 2020 and its projections for 2021.

2.1 Impact for 2020

According to the latest official data (only first quarter of 2020 measured) (Haut Comissariat au Plan (HCP), 2020a), Morocco is experiencing its first recession in more than two decades. Worse than the financial crisis of 2008, this global pandemic has had important effects on national economic activity. Several key sectors have suffered the adverse consequences of this health and economic crisis, mainly in the tourism, transport, and industrial sectors. The latter has suffered in particular from the fall in international demand, especially from the European continent, which is the first trade partner of the Moroccan economy.

The 2019/2020 agricultural year was characterized by a rainfall deficit for the second consecutive year, with rainfall limited to 253 mm, bringing the level of filling of dams to 48% as compared to 65% in the previous year.

As we will see in Table 1, rainfall deficit has also impacted cereal production, estimated at 30 million quintals (−42% compared to the previous crop year). This decrease in cereal production, combined with the decline in maritime fishing activities, was estimated to result in a 5.7% decline in 2020 (compared to a 4.6% decline in 2019) thus contributing once again negatively to gross domestic product (GDP) growth by −0.4 points.

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[1] For example, during this period Public transport could be filled up to 75% of their capacity. Hotels could be occupied at a maximum rate of 50%.

Table 1 Estimated impact of the pandemic on main economic sectors and contribution of each sector to GDP

Sectors	Value added growth 2019/2018 (%)	Estimated value added growth 2020/2019 (%)	Sectoral value added weight in GDP[a] (average value 2007–2019) (%)
Primary sector (agriculture + fishing)	4.6	−5.7	13[b]
Transformation industry	2.8	−5.6	14
Mechanical metallurgical and electrical engineering industries	4.7	−7.9	4
Food industry	1.1	−2	4
Textile and leather industry	3.1	14.6	2
Chemical and para-chemical industries	5.6	2	2
Building and public works	1.7	−12	5
Mining industries	1.1	2.4	2
Energy industries	13.2	−11	2
Tourism	3.7	−5	2
Transport	6.6	−8.9	4
Retail and other services	2.4	−4.7	9
Post and telecommunication services	0.3	6.1	5
Non-market activities	5	2.3	32
GDP in volume	*2.5*	*−5.8*	*100*

From Haut Comissariat au Plan (HCP) (2020a) for value added estimations and Haut Comissariat au Plan (HCP) (2020b) for the contribution of each sector to GDP

[a] The contribution of each sector to GDP has not significantly changed from 2007 to 2019. For this reason, an average value is displayed. The weight corresponds for each sector to the value added of the sector/GDP

[b] 12% for agriculture and 1% for fishing activities

Due to the decline in foreign demand, particularly from the European Union, and due to the disruptions in the logistics and input supply chains, the value added of transformation industries was estimated to have declined of nearly 5.6% in 2020 after a 2.8% increase in 2019.

Under these conditions, the activities of the mechanical metallurgical and electrical engineering industries suffered from an estimated decline of 7.9%, compared with a 4.7% increase in 2019. The automotive sector, which accounts for 27% of total exports, is also expected to be strongly affected by the crisis, since assembly production depends heavily on inputs imported from other countries where several plants were shut down.

Similarly, the aeronautics sector, operating in a globalized value chain, is expected to be largely affected by the decisions to close aircraft equipment manufacturers' plants abroad and by the crisis in the airline industry.

The value added of the food industry reports an estimated decline of 2% in 2020, after an increase of 1.1% in the previous year.

As for the textile and leather industry, activity is expected to record a drop of 14.6% in 2020 in its value added against an increase of 3.1% in 2019. This decline is a result of the drop in demand (logistics issues), particularly in Spain and France. Both countries absorb nearly 60% of the sector's exports.

The activities of the chemical and para-chemical industries are expected to show some resilience, recording a 2% improvement in their value added in 2020 after 5.6% recorded in 2019. In particular, the export-oriented chemical fertilizer industry is expected to benefit from an increased demand from Brazil and some Africa countries, notably from Nigeria and Ethiopia.

The value added in the building and public works sector is expected to decline by 12% in 2020.

For the mining sector, value added is expected to slow down, recording a growth rate of 1.1% in 2020 instead of 2.4% in the previous year. The slowdown in the market production of rock phosphate would result from the crisis effect on the external demand for phosphate and its derivatives, in a context marked by a drop in their prices at the international level.

The value added of the energy sector estimated decline is 11% in 2020 against a net rebound of 13.2% recorded a year earlier. This drop is mainly due to the slowdown in industrial activities and a decrease on external demand for electricity, particularly from Spain.

Due to lockdown and the closure of air and sea borders to passengers, the tourism sector is the most affected by the crisis. Faced with an almost total shutdown in activity since mid-March 2020, this sector is experiencing a very difficult year. The value added of the sector is estimated to decline of 57%, compared with a positive growth rate of 3.7% a year earlier. This situation is expected to lead to a collapse in tourism revenue and major job losses. The recovery of the sector is likely to be very difficult, given the restriction on travel from other countries and the possibility of a second wave in the last quarter of 2020.

Being strongly correlated with tourism activity, the transport sector is being impacted due to limited inter- and intra-country mobility. The value added of the transport sector is expected to decline by 8.9% in 2020 as compared to the 6.6% recorded increase in 2019.

Due to the transition of a large proportion of employees to teleworking and the need to continue distance learning, the value added of the postal and telecommunications sector is estimated to grow by nearly 6.1% in 2020 compared to 0.3% in 2019.

Table 2 Impacts of value added in Q1, Q2 and expected impact in Q3 2020

Sector	Q1 2020/Q1 2019 (%)	Q2 2020/Q2 2019 (%)	Q3 2020/Q3 2019 (%)
Agriculture	−5	−6.1	−5.9
Non-agricultural activities	0.9	−14.4	−4.1
Mining	−0.4	3.7	0.1
Secondary sector	0.2	−14.3	−5.8
Tertiary sector	1.6	−11.5	1.6
GDP	*0.1*	*−13.8*	*−4.6*

From Haut Comissariat au Plan (HCP) (2020c)

The value added of non-market services (such as education and insurance) is expected to grow by 2.3% in 2020, although at a slower pace than the 5% recorded in 2019.

Under these conditions and taking into account an expected drop in taxes and duties on products net of subsidies of 9%, the gross domestic product, would record a decrease in volume of 5.8% in 2020 instead of the 2.5% growth recorded in 2019.

The expected values of the impact of the crisis on annual growth published by the High Commission for Planning (HCP) are based on economic results for the first and second quarter of 2020 (respectively Q1 and Q2) and projected growth rate in the value added of the main sectors for the third quarter of 2020 (Q3) (Haut Comissariat au Plan (HCP), (2020c)). These quarterly results are displayed in Table 2.

2.2 Expected Impacts for 2021

In the exploratory budget of 2021, the High Commission for Planning established the first economic outlook for the year 2021. The forecast assumed the end of the effects on economic growth of the COVID-19 pandemic by December 2020 and was based on an average scenario of agricultural production during the 2020/2021 season. Even if this is not exactly the case, since the end of full lockdown in June, there has not been a new lockdown. Instead, a curfew time has been established (first at 11 pm, then at 8 pm) but, differently from some European countries, all schools, restaurants, cafes, and other non-essential sectors have stayed open. The forecast also takes into consideration the new trends of the international environment after the crisis, in particular the evolution of raw material prices and global demand addressed to Morocco. The latter is expected to improve by nearly 12.2% in 2021 instead of a 16.2% drop in 2020. In addition, a resumption of transfers from Moroccans living abroad and foreign direct investment is also expected after their decline in 2020.

Based on these assumptions, the value added of the primary sector is expected to grow by about 9.1% in 2021 instead of a 5.7% decline expected in 2020.

Table 3 Expected growth in GDP and main sectors by 2021

Sector	Value added growth, 2020/2019 (%)	Value added growth, 2021/2020 (%)
Primary sector	−5.7	9.1
Non-agricultural activities	−5.3	3.6
Secondary sector	−6.9	4.6
Tertiary sector	−4.5	3.1
GDP in volume	*−5.8*	*4.4*

From Haut Comissariat au Plan (HCP) (2020a)

Non-agricultural activities would record a moderate growth rate of about 3.6% in 2021 instead of a 5.3% decline in 2020, due in particular to the slow growth of the services and construction sectors and the transformation industries. Benefiting from the good performance of mining activities, chemical and para-chemical industries, and food transformation industries (due to the expected improvement in external demand), the value added of the secondary sector is expected to an increase of 4.6% in 2021 compared to a negative growth of 6.9% in 2020. Instead, the activities of the mechanical, metallurgical, and electrical industries will suffer from the persistent underperformance of the automobile and aeronautics sectors at the world level.

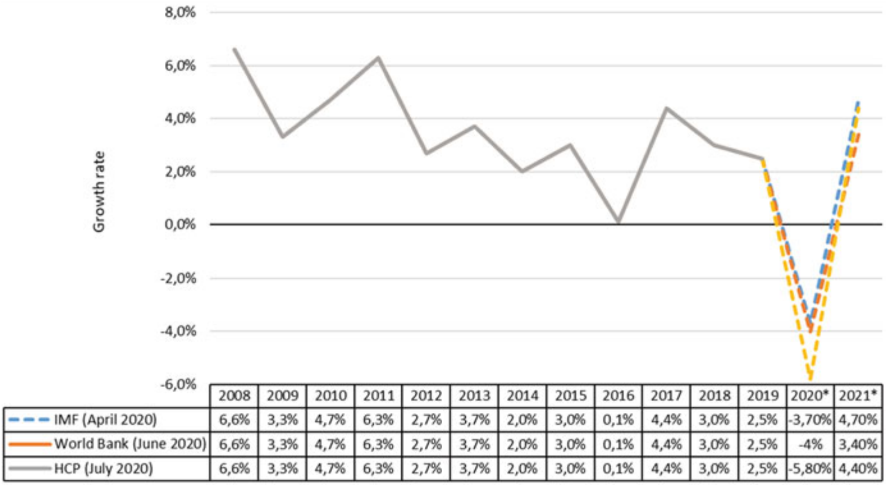
The building sector and the construction of public infrastructure are expected to continue suffering from the negative impacts of the crisis, with an expected recovery of nearly 5.9% in 2021 after a 12% drop in the value added of the sector in 2020. In particular, the building sector is expected to be the most difficult to recover from this category.

Finally, the tertiary sector is expected to record a timid growth of around 3.1% in 2021 as compared to 4.5% decline in 2020 following the very slow and gradual recovery of service activities, particularly tourism, transport, and trade.

Taking into account a 4.9% increase in taxes and duties on products net of subsidies, gross domestic product is expected to growth 4.4% in 2021 after a recession of 5.8% in 2020 (Table 3).

As a result, economic growth is expected to increase of 4.4% in 2021 as compared to the 5.8% decline in 2020. This recovery is expected to be mainly driven by the good performance of mining activities, chemical and para-chemical industries and food processing industries, and the gradual recovery of foreign demand addressed to Morocco.

This forecast is subject to great uncertainty, especially in the case of global pandemic. Some international institutions have published economic outlooks for the next 2 years. In April 2020, the International Monetary Fund published its first projections for 2020 and 2021 (International Monetary Fund (IMF), 2020b) and updated its projections in June 2020 (IMF, 2020). The revised projections have underlined an economic fallout stronger than anticipated. The IMF projections of global growth show a decrease of 4.9% in 2020, 1.9% points below the April 2020 World Economic Outlook (WEO) forecast. With a negative impact on activity in the first half of 2020 that was worst than anticipated, the recovery is projected to be



	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020*	2021*
- - - IMF (April 2020)	6,6%	3,3%	4,7%	6,3%	2,7%	3,7%	2,0%	3,0%	0,1%	4,4%	3,0%	2,5%	-3,70%	4,70%
— World Bank (June 2020)	6,6%	3,3%	4,7%	6,3%	2,7%	3,7%	2,0%	3,0%	0,1%	4,4%	3,0%	2,5%	-4%	3,40%
— HCP (July 2020)	6,6%	3,3%	4,7%	6,3%	2,7%	3,7%	2,0%	3,0%	0,1%	4,4%	3,0%	2,5%	-5,80%	4,40%

Fig. 1 Alternative estimations for the Moroccan economic growth. (From Haut Comissariat au Plan (HCP), 2020c; World Bank, 2020; IMF, 2020). (The April version is considered instead of the updated June version because the latest does not give estimates for Morocco.)

more gradual. In 2021 global growth is projected to increase by 5.4%. Advanced economies are expected to be more severally hit with a growth rate of −8% in 2020 and 4.8% in 2021, whereas in emerging markets and developing economies, these growth rates are expected to reach −3% and 5.9% in 2020 and 2021, respectively.

In June 2020, The World Bank published a new report on global economic prospects (World Bank, 2020) proving a near term outlook of the global economy. The World Bank expects a negative growth of −5.2% in 2020 with a recovery in 2021 of 4.2%. Advanced economies are expected to experience a negative growth of −7% in 2020 and a positive recovery of 3.9% in 2020. Emerging markets and developing economies are expected to be less affected with a negative growth of −2.5% in 2020 and a positive growth of 4.6% in 2021. In the Middle East and North African regions, these values are expected to reach −4.2% and 2.3% in 2020 and 2021, respectively (Fig. 1).

The most updated estimate is the one established by the Moroccan institution, which is also the one that results in a more pessimistic recovery. The difference between the first version of the IMF outlook and the most recent estimation of the HCP is around 2% of GDP growth for 2020. Instead, the projected growth rate for 2021 is less variable among the different forecasts, with a moderate recovery according to the World Bank projections compared to those of the IMF and the HCP. For the remaining, only the World Bank and the HCP projections for Morocco are considered as they are the most updated ones.

In order to compare the expected impact of the crisis in Morocco with other regions in the world, growth projections for the European Region (main trade partner of Morocco) and of the World are displayed in Fig. 2. In addition, single

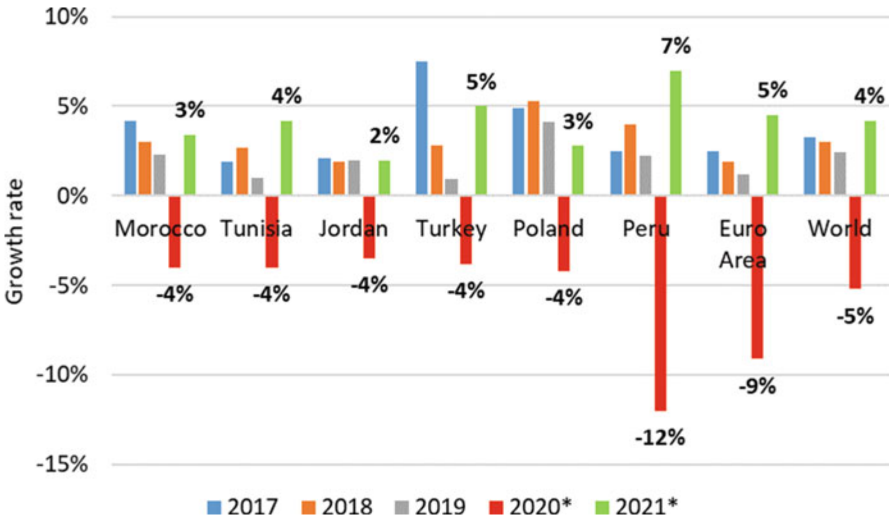


Fig. 2 Growth rates in selected economies, where the rate for 2021 is estimated. (From World Bank, 2020)

countries such as Tunisia, Jordan, Turkey, Poland, and Peru are also selected for comparison. These countries were chosen due to some similarities with the Moroccan Economy (including the energy sector for most of them). More details about the economies of the selected countries are available in Appendix 1. To provide a coherent comparison of growth rates, only data from the World Bank outlook (World Bank, 2020) are considered, from 2017 to 2021.

In general, estimations are similar for Morocco, Tunisia, Jordan, Turkey, and Poland with a more optimistic recovery for Turkey in 2021. The impact of the crisis in these countries is expected to be close to the expected impact for the whole World. However, Peru was estimated to be hardly impacted in 2020 with a negative growth rate of 12% and a positive recovery of 7% in 2021.

3 Long-Term Impact of the Pandemic on Electricity Demand Growth

Herein we use the information of sectorial contribution to GDP in Table 1, electricity intensity of sectors provided by IEA (2020a) and hypothesis on alternative scenarios of economic recovery to build three post-pandemic scenarios for electricity demand up to 2030. With this purpose, we first aggregate those sectors into four: agriculture, industry, transport, and services (Table 4).

Table 4 Aggregation of sectors

Agriculture	Agriculture
Fisheries	
Extractive industries	Industry
Transformation industries	
Food industry	
Textile and leather industry	
Chemical and Para-chemical industry	
Metallurgic, mechanical, and electrical industry	
Other industries and oil refineries	
Electricity and water	
Buildings and public works	
Transports	Transports
Commerce	Services
Hotels and restaurants	
Telecommunications	
Activities of financiers and insurance	
Services to individuals and firms	
Public administration	
Education, health	

Own elaboration based on HCP (2020a)

Table 5 Percentage contribution to GDP based on the average of data from 2007 to 2018

Year	Agriculture	Industry	Transport	Services
Average contribution to GDP (%)	13	36	4	47

Based on HCP (2020a)

Then we retrieve from HCP (2020a) the value added for all the sectors detailed in Table 1 from 2007 to the first quarter of 2020 and aggregate them calculating their average contribution per sector to GDP. We present the results in Table 5.

Then, using the Electricity balance provided from IEA (2020a) for those four aggregated sectors, we calculate the electricity demand for each sector obtaining the values hereafter (Table 6).

Comparing the values in Tables 5 and 6 we observe that energy intensity is stable in each of the four sectors across the 11 years studied. The ratio between GWh consumed and value added are respectively: 0.025 for agriculture, 0.034 for industry, 0.01 for transport, and 0.012 for services.

We then define scenarios for GDP increase up to 2030 based on the estimations of the HCP (2020c) and considering the estimations of the World Bank and IMF, and, using the energy intensity calculated, we are able to define scenarios for sectoral contribution to GDP and electricity demand (this simple methodology is based on Durand (2012)). The scenarios for GDP growth and sectoral contribution to GDP are described hereafter (Tables 7 and 8).

We use the baseline scenario as a hypothetical reference where we assume the perpetuation of the growth rate that the economy had before the pandemic occurred

Table 6 Electricity consumption per sector

GWh consumed	Agriculture	Industry	Transport	Services
2007	2246	8543	241	2961
2008	2322	8091	253	3793
2009	2396	8365	267	3921
2010	2537	8852	281	4149
2011	2739	9555	302	4479
2012	2941	10,244	320	4802
2013	3183	10,304	322	4911
2014	3353	10,660	332	5030
2015	3487	10,864	345	5092
2016	3898	11,190	352	5154
2017	3719	11,825	368	5580
2018	3366	12,086	375	5640

Own elaboration based on IEA (2020a) database

Table 7 GDP growth assumptions for three alternative post-pandemic scenarios

	2020 (%)	2021 (%)	2022–2025 (%)	2026–2030 (%)
Baseline	4.1	4.1	4.1	4.1
Post-pandemic scenarios				
Central	−7	5.8	4.1	5
Optimistic	−7	7	5	5.5
Pessimistic	−7	4	4.1	4.1

Table 8 Share of sector's contribution to GDP growth for alternative scenarios

Optimistic	*2020–2021*	*2022–2025*	*2026–2030*
VA agriculture	13%	12%	11%
VA industry	36%	35%	34%
VA transport	4%	4%	4%
VA services	47%	49%	51%
Central	*2020–2025*	*2026–2030*	
VA agriculture	13%	12%	
VA industry	36%	35%	
VA transport	4%	4%	
VA services	47%	49%	
Baseline and pessimistic	*2020–2030*		
VA agriculture	13%		
VA industry	36%		
VA transport	4%		
VA services	47%		

and that the value added of each sector as well as its energy intensity is constant until 2030. The central scenario considers the estimation for 2020 for the Moroccan High Commission for Planning and continues the trend of their growth forecast for

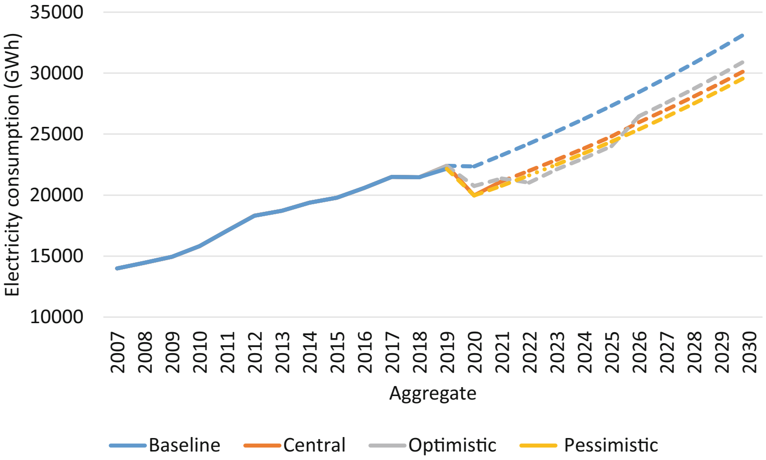


Fig. 3 Scenarios of electricity demand up to 2030. (Own elaboration based on HCP data)

2021 up to 2025. Then it considers an acceleration of growth from 2026 to 2030 inspired on The World Bank estimations. We also assume that as from 2026 non-manufacturing industries with low value added decrease their participation in GDP. For the optimistic scenario, we assume a stronger rebound in 2021. The scenario assumes a progressive acceleration of economic convergence starting from 2022 to 2025, followed by a period of deeper transformation of the economy in the period 2026–2030 with an acceleration of growth. In this scenario, the structure of the economy shifts to a service economy at a stronger pace than in the previous scenario, supporting the process of economic convergence of countries. Finally, for the pessimistic scenario we consider a lower rebound effect in 2021 (based on the World Bank latest forecasts) and a slow transformation of the economy before 2030 without any acceleration of growth or change each sector's contribution to GDP. The result for each sector in terms of trends up to 2030 is displayed in Appendix 2. Herein we cite the resulting aggregate forecast for electricity demand up to 2030 is in Fig. 3.

Figure 3 shows that not even in the case of a recovery with an important catch up effect and with an increase in GDP participation of the sectors that are more likely to grow (optimistic scenario), the recovery reaches the before-pandemic trend. Indeed the crisis due to the pandemic has a long-term effect on electricity demand, which represents both a challenge for GDP growth and an opportunity for a more efficient energy transition in the recovery.

4 Short-Term Impacts of Lockdown in the Electricity Sector

According to the latest official publications of the impact of the crisis on the Moroccan power sector (Direction du Trésor et des Finances Extérieures, 2020), local electricity production fell by 6.6% at the end of April 2020 compared to +28.3% a year earlier, in April 2019. This trend stems from a decrease ranging from −2.3% for non-conventional renewable energies and −11.5% for Moroccan state owned single utility (called ONEE) production.

Whereas electricity exports to Spain had increased significantly in 2019 following the closure of several thermal power plants in Spain, the balance of energy exchanges with Algeria and Spain decreased in 2020.

Comparing the end of April 2020 with the same date in 2019, electricity consumption fell by −2.2% compared to −0.6% a year earlier. Consumption in the medium voltage fell by −1.9%. Electricity distributed to the "Régies"[2] and consumption in the high and very high voltage fell by −4% and −16.5%, respectively. Finally, consumption in the residential sector increased by 6%.

The energy bill fell by 0.6 billion US$[3] or 21.1% in April 2020, compared to April 2019, due to the fall in oil prices in the international market by 33% to US$44/bbl.

5 Impact of Lockdown on Load Curve

Lockdown was announced on the 18th of March, started on the 20th of March at 8 pm and went on until the 12th of June. To study the immediate impact that the lockdown had on electricity demand, we compare the week before lockdown with the week after lockdown to be sure that the same economic climate and weather were present. Demand decreased on average by 16.41% as we can see in Fig. 4.

Considering the first quarter of the year, which includes lockdown (period 01/01 to 19/05), electricity demand decreased by 4% in 2020 as compared to 2019, reaching 14.7 TWh in 2020. For 2 months of lockdown, electricity demand decreased by 12% on average as compared to 2019, with a decrease of around 11% in the period 18/03 to 18/04 (first month of lockdown without Ramadan in both years considered) and almost 13% in the period 19/04 to 19/05 (second month of lockdown with Ramadan during 2020 but without it in 2019).[4]

Looking at Fig. 4 we also observe a slight change in the shape of the load during the day. We explore this in Fig. 5.

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[2] Local municipal authorities.

[3] 5.5 billion DH = 0.6 billion dollar (1DH = 0.11$).

[4] For a detail on disentangling the impact of Ramadan from the impact of lockdown, see Appendix 3.

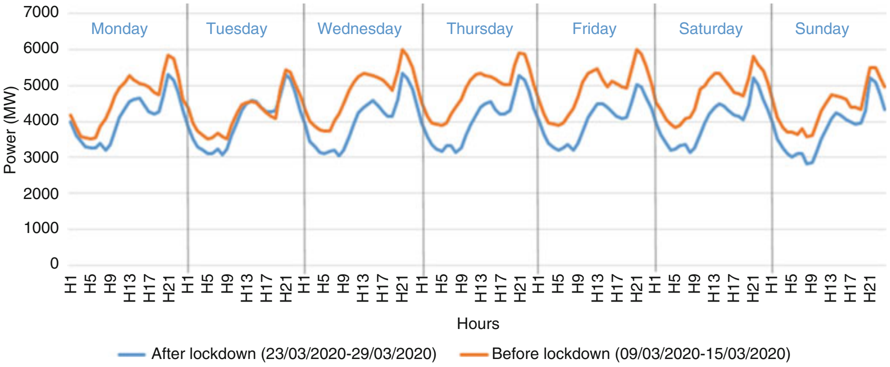

Fig. 4 Comparison of electricity demand for the week before and after lockdown. (Own elaboration based on HCP, 2020a)

Fig. 5 Weekly variation of baseload ($P_{\min}$) and peakload ($P_{\max}$) 2020/2019. Week 11 corresponds to the beginning of lockdown. (Own elaboration based on HCP, 2020c)

Except for the first week of the year where the baseload ($P_{\min}$) and the peakload ($P_{\max}$) decreased in 2020 as compared to 2019, the rest of the time the load showed a higher baseload and peakload as compared to 2019, with a more remarkable increase in baseload ($P_{\min}$) than in peakload ($P_{\max}$). Starting from week 11 that corresponds to the beginning of lockdown, both $P_{\min}$ and $P_{\max}$ follow a decreasing trend, with a much higher decrease in baseload than in peakload. In average, and before lockdown, weekly baseload increased by 4%, whereas peakload increased by only 2% compared to 2019 level. During the lockdown period, baseload decreased by 14% and peakload decreased by 8%. These variations show indeed that the lockdown decreases electricity demand in average but also seems to flatten the curve.

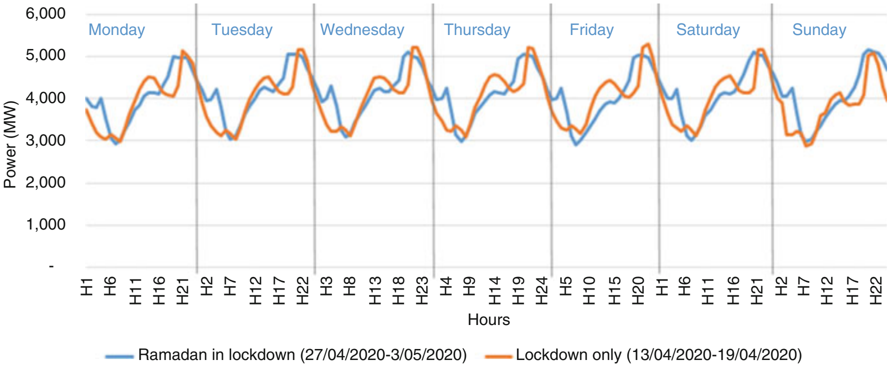

Fig. 6 Ramadan impact in 2020 during lockdown. (Own elaboration on HCP, 2020c)

One month after lockdown started (from the 24 April to 23 May), Morocco like other Muslim countries celebrated the Ramadan month.[5] Such a festivity changes the time of use of electricity since people prepare meals only during the night and stay awake later. To account for the interaction between lockdown and Ramadan on electricity consumption, in Appendix 3 we studied the impact of Ramadan on electricity demand before the pandemic, using the available historical data (2017 and 2019). The fact that Ramadan produced, on average, an increase in demand in 2019 and a decrease in 2017 does not allow us to take a clear conclusion on what to expect in terms of average demand variation regarding Ramadan in 2020, and consequently, we do not know how to disentangle that effect from the lockdown effect. On the other hand, there are a few stylized facts that can be extracted from the analysis in Appendix 3: electricity demand is higher during Ramadan before 4 am and the shape of electricity demand is flatter during Ramadan from 10 am to 7 pm.

Then, this means that after the 16th week in Fig. 5, the flattening impact of lockdown on the load may be accentuated by the effect of Ramadan that started on that week. To further explore this impact in Fig. 6, we explore the impact of Ramadan in 2020 during lockdown.

Figure 6 shows that indeed the midday peak almost disappears during Ramadan and, as expected, the load curve is flattened with a lower peakload observed for every day except Sunday.

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[5] Ramadan is a month of fasting during the day, prayer and family gathering during the night.

6 Concluding Remarks

In this chapter we have studied the short- and long-term impact of the COVID pandemic on the electricity demand in Morocco. The short-term impact of the strict lockdown where very important decreasing demand in average of almost 14% and flattening the curve. This curve flattening has been accentuated by the impact of Ramadan that induces a change in the time of electricity use.

The long-run impact of the COVID pandemic is also very strong. We find that even in the most optimistic scenario where we consider a catch up effect in GDP growth as well as an economy that is more axed on industrialized sectors as opposed to agriculture; demand stays lower than before the pandemic. This stays true up to 2030. This finding is in line with what most of the literature predicts in terms of long-run effects of the pandemic.

Appendix 1: Trends in countries used for comparison

In its latest report (2018) on multidimensional review of Morocco (OCDE, 2017), the OECD selected 11 countries to support the analysis of Morocco's performance, accompanied by a brief description of the most relevant economic and political aspects. In the report, these countries were selected on the basis of their level of development, as measured by their GDP per capita, and the degree of success of their economic policies, which can be considered as models or sources of inspiration for Morocco. The selection also focused on the similarity of countries' economic structures, particularly in terms of natural resource endowment, degree of industrialization or export structure. The population, the degree of social and spatial inequality, and the size of the territories were also included as identification criteria in order to compare Morocco with countries with similar characteristics. In this chapter, selected countries share also similarities in the energy sector with Morocco in addition to their similarities in terms of economic structure.

Tunisia

Geographically very close, Tunisia and Morocco have been cultural, historical, and economic partners since the independence of the two countries in 1956. Their relations of cooperation are governed by a legal framework of more than 50 agreements and conventions. The Tunisian Revolution of 2010–2011, which marked the beginning of Spring has had a strong impact on the economic and political situation of the country. The Tunisian economy is today dominated by the services and industry, with the weight of the agricultural sector constantly declining but still comparable to Morocco (15% and 16% of GDP respectively) (OCDE, 2017).

Tunisia shares with Morocco the same social challenges: youth unemployment and significant regional disparities. Like Morocco, Tunisia is an energy importer.

Jordan

In a regional context impacted by several crises, Jordan attempts to maintain a stable political and diplomatic relationships with its neighbors. Since the end of the 1980s, Jordan has conducted several reforms to achieve economic modernization. During the 2000s, Jordan recorded a strong growth rate, around 8% between 2004 and 2008, mainly driven by financial services. Like Morocco, Jordan has very limited energy resources, which requires it to import more than 95% of its energy needs. The energy bill represents almost 20% of GDP (OCDE, 2017). Jordan has recently completed important reforms in the energy sector to diversify its sources of supply and develop renewable energy production (wind and solar).

Turkey

Since the financial crisis of 2001, Turkey has carried out a series of rapid financial and banking reforms. The country has conducted several business-friendly reforms and based its development on the export of industrial products while keeping public spending under control. Following these measures, the GDP per capita of Turkey has doubled in 10 years, between 2002 and 2012 (OCDE, 2017). The country is now a major producer and exporter of agricultural products, textiles, and construction equipment. Morocco and Turkey have been linked by a free trade agreement since 2006 in which Morocco exports phosphates and imports equipment appliances. Like Morocco, Turkey imports more than 70% of its energy needs (OCDE, 2017).

Poland

After the fall of the communist regime and its adhesion to the EU in 2004, Poland has conducted several reforms to modernize its economy and achieve the transformation to a market economy. The country's economy is based on a broad industrial base (almost a quarter of the value of the country's GDP) (OCDE, 2017) especially regarding the processing of intermediate products. In addition, Poland has also succeeded the diversification of its economy with the development of the sector of services. From an energy point of view, Poland shares with Morocco its dependence on coal to meet its electricity needs even if Morocco has adopted a strategy for electricity supply diversification starting from 2009, based on renewable energy production.

Peru

Over the past two decades, Peru has recorded solid economic growth, averaging 5.3% per year between 2000 and 2014 (OCDE, 2017). This situation has been accompanied by an improvement of the poverty rate and the emergence of a middle class. Peru has conducted a process of industrialization based on economic openness and is striving to diversify its economy with the development of the sector of services. In spite of strong macroeconomic performance, the Peruvian society is still characterized by high inequality (especially between urban and rural citizens), both in terms of income and well-being. For example, the Gini coefficient in Peru is estimated at 0.45 (2013), in line with the coefficient in Morocco estimated at 0.40 (2014). Moreover, as it is also the case in Morocco, the economy of Peru is marked by the weight of the informal economy.

Appendix 2: Scenarios per Sector

We describe the demand forecast by sector resulting from these scenarios in Fig. 7. and the aggregate result of the long-term impact of the pandemic on electricity demand up to 2030 is presented in the main text.

Annex 3: The Impact of Ramadan in the Load Curve

To disentangle the impact that Ramadan may have had on demand during the lockdown period, we first explore the historical impact of Ramadan in electricity demand.

Ramadan Reduced Electricity Demand in 2017

To study the impact of Ramadan alone, we compare hourly electricity demand for a week during Ramadan 2017 and for a week immediately before Ramadan that same year (29/05/2017 to 04/06/2017 vs. 22/05/2017 to 28/05/2017). This comparison shows that weekly electricity demand is 2% lower in the week of Ramadan (764 GWh) compared to the week without Ramadan (777 MWh).

The drop in weekly electricity demand in Ramadan is mainly driven by the decrease in electricity demand during working days. On average, demand decreased on a Ramadan Monday of 4% (from 108 to 112 GWh) with an average decrease of around 2% for all working days (from 553 to 566 GWh). However, in the weekend

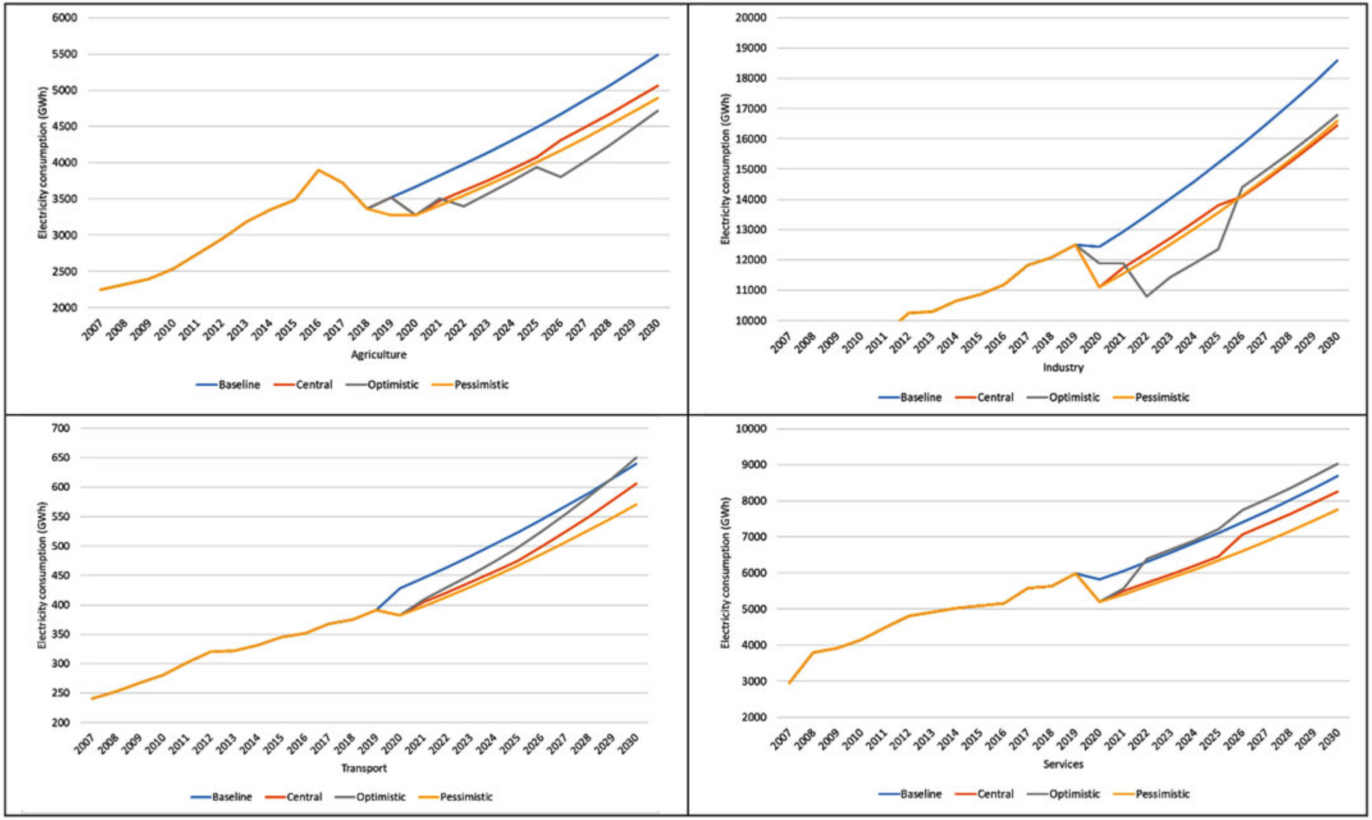

Fig. 7 Sectorial scenarios up to 2030. (Own elaboration)

the average electricity demand remained relatively stable around 211 GWh in both periods.

The average baseload power during a week in Ramadan 2017 is 3537 MW as compared to 3618 MW without Ramadan. The maximum peak power is respectively 5265 and 5586 MW.

Looking at the intraday hourly variation of electricity demand, the results show that the pattern of electricity demand between a Ramadan and a non-Ramadan day is quite similar, especially during the weekend. The shape of the load does not change significantly. The mid-day and the evening peak hours remain the same (Fig. 8). Before 5 am on Monday, electricity demand in Ramadan is slightly higher as people prepare their last meal before fasting[6] during the day. Then electricity demand in Ramadan remains lower during the remaining hours of the day as compared to a non-Ramadan day. Instead, on Sunday electricity demand seems Ramadan has no significant impact.

Ramadan Increased Electricity Demand in 2019

To analyze the Ramadan effect in 2019, we followed the same methodology as before. We therefore compare a week before Ramadan and a week during Ramadan (27/05/2019 to 02/06/2019 vs. 13/05/2019 to 19/05/2019). In this case, the total weekly electricity demand increased by 10% in Ramadan (from 853 to 771 GWh) with an average increase of 11% during working days (from 615 to 556 GWh) and 10% in the weekend (from 237 to 215 GWh).

On Monday and during Ramadan, total electricity demand increased by 7% (from 122 to 113 GWh) compared to Monday with no Ramadan, whereas it increased by 9% (from 115 to 105 GWh) in Sunday in Ramadan compared to a Sunday in a non-Ramadan week.

The average baseload power during a week in Ramadan is 3940 and 3857 MW in a non-Ramadan week. The maximum peak power is respectively 5872 and 5703 MW.

Contrary to 2017, electricity demand increased in 2019 in Ramadan compared to a non-Ramadan period, even if both week compared in 2019 and 2017 are in May. One explanation for this observed difference may be attributed to weather conditions as 2019 recorded very high temperatures in Morocco.[7] With contradictory results (increase vs. decrease in electricity demand in Ramadan), available data for 2017 and 2019 does not allow to conclude on the effect of Ramadan on electricity demand. However, based on Figs. 8 and 9, it seems that Ramadan flattens the load shape between 10 am and 7 pm.

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[6] Fasting starts after the Fajr prier at dawn (between 3 am to 5 am depending on the year).

[7] Leading to a high electricity consumption due to air conditioning use.

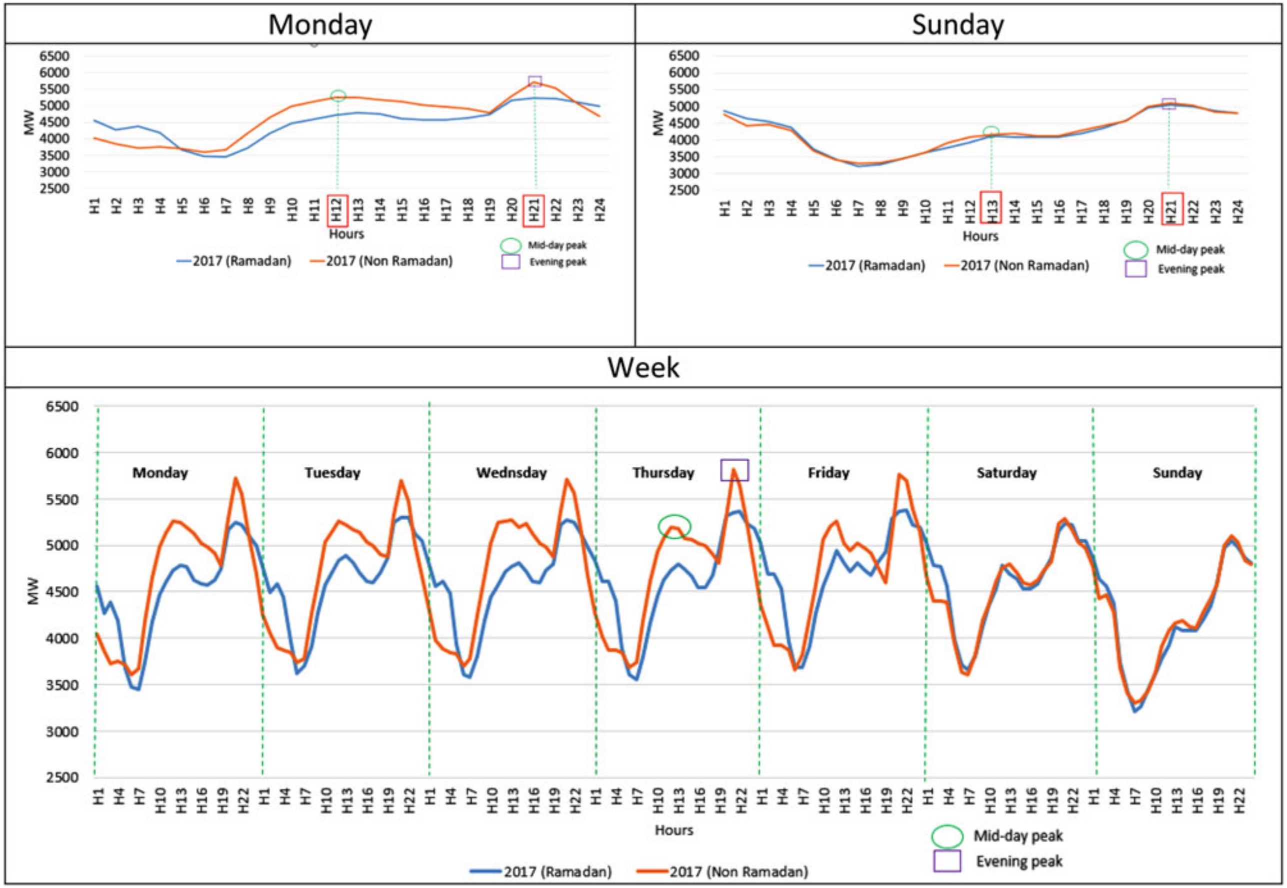

Fig. 8 Electricity demand in representative week/days of 2017 during Ramadan and non-Ramadan periods. (Own elaboration based on HCP, 2020a, c)

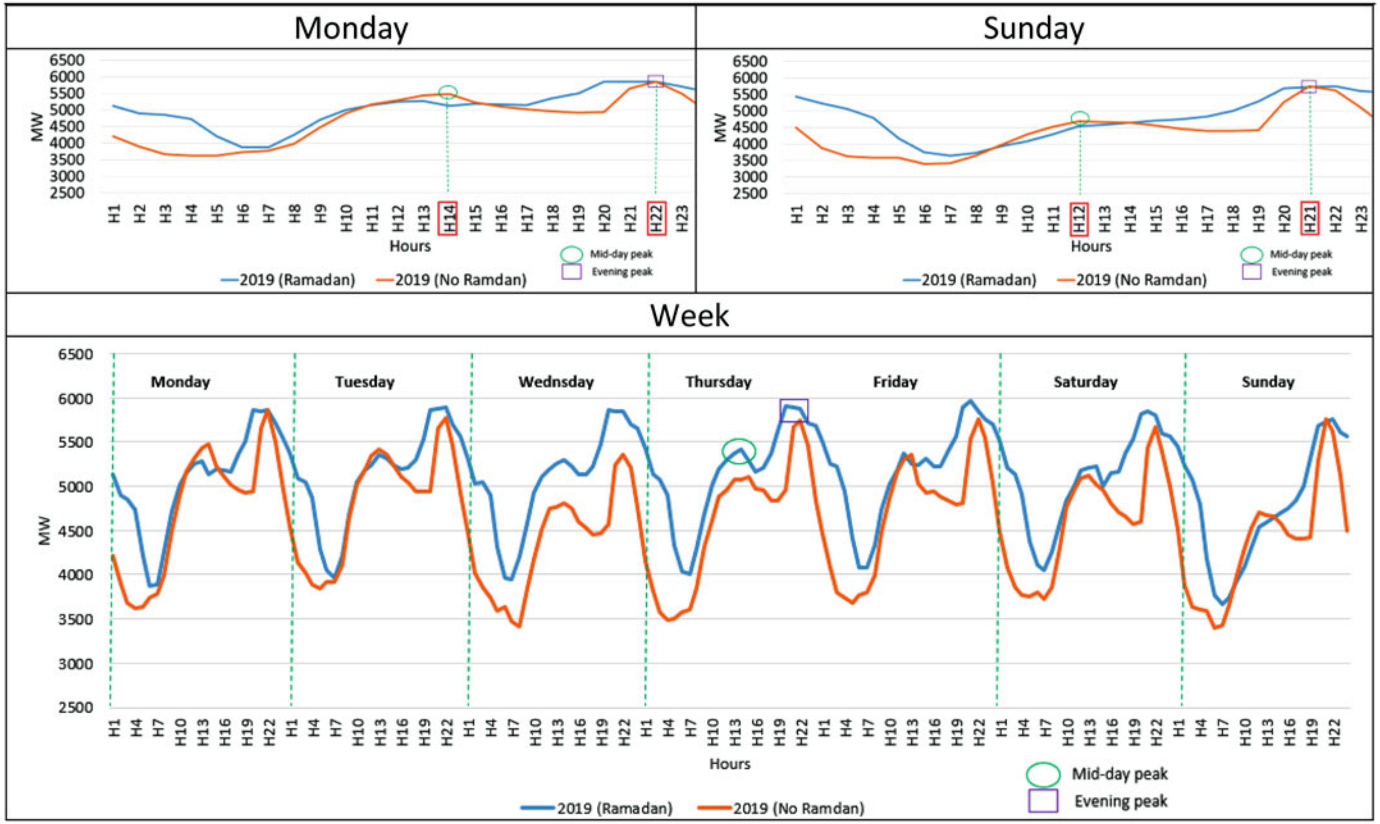

Fig. 9 Electricity demand in representative week/days of 2019 during Ramadan and non-Ramadan periods. (Own elaboration based on HCP, 2020a, c)

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A Proposition Relationship Between Green Workplace Environment and Employees Green Behavior on Organizational and Environmental Impacts

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1 Introduction

In light of the coronavirus pandemic (COVID-19), green business practices got more attention from entrepreneurs and professionals, which is an essential solution to ensure business continuity and avoid business failure due to the increasing public health regulations (Amankwah-Amoah, 2020). Thus, this chapter emphasizes the employees' perceptions of green workplace environments' importance on organizational and environmental impact. It addresses how both management and staff perceive and look at the role of green workplace environments in the existence of new practices such as social distancing, hand sanitizing, and face masks. In ability, motivation, and opportunity (AMO) theory, Singh et al. (2020) argued that firms' human resource management (FHRM) seeks to attract talented workers, motivates them to maintain their job performance, and environmentally improves their knowledge and skills to fit green innovation practices, thus enhancing organizational performance. Based on dynamic capability view Teece (2016) viewed firms that are aiming to explore green opportunities and develop their green business strategies should environmentally address those concerns. This leads firms to search and reconfigure their business plans on innovation-based environmental systems.

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The dynamic capability view suggests that firms reconfigure their green practices and develop employees' green behavior to meet environmental challenges. Through the learning process and experiences, the study viewed that employees and management can upgrade their capabilities to fit the ecological problems raised in light of COVID-19. An empirical study by Kato et al. (2009) examined the impact of a green workplace environment on individuals' perceptions. The results indicate that a green workplace environment offers more incredible psychological benefits than physical improvements such as productivity and health gain. These results show that during such circumstances like the COVID-19 pandemic, the green workplace's importance tends to be crucial to employees' job satisfaction and organizational and environmental impacts.

Besides, researchers (Francoeur et al., 2019; Morgan & Rayner, 2019) argued that employee behavior in the green workplace could be seen as a motivational factor for increasing occupiers' environmental awareness and skills. In practice, Homburg and Stolberg (2006) note that employees directly influence firms' workplace environment by reducing energy consumption and indirectly encouraging organizational members to adopt and leverage green behavior.

Few studies such as Rayner and Morgan (2018) and Singh et al. (2020) argued that human resource management is responsible for leveraging green practices. This, in turn, leads to improve green workplace (Morgan & Rayner, 2019) and enhances employee satisfaction (Bangwal & Tiwari, 2019). Consequently, firms might be able to achieve superior organizational performance and respond to environmental requirements. A fundamental premise of this present research is aligned with the view that being greener is environmentally crucial for business (Crotty & Rodgers, 2012), especially during the worldwide epidemic. Furthermore, occupiers acquire a central role in deploying green practices (Huffman & Klein, 2013), which fosters ecosystem sustainability and green behavior such as waste avoidance (Dilchert & Ones, 2012). This research highlights the significance of using green practices as a strategic solution culture to encounter COVID-19 challenges and fulfill governmental and societal requirements and conditions to reduce coronavirus spread. Furthermore, this study aims to address the new practices that influences the firm's business strategy and employees' skills and behaviors during COVID-19 from the green practices point of view by linking and proposing several hypotheses.

The majority of past studies (Albort-Morant et al., 2016; Bai et al., 2019; Chen et al., 2006; Kong et al., 2016; Kraus et al., 2020a, b; Nasrollahi et al., 2020; Rehman et al., 2020) focused on an organizational level in addressing green practices and its relation on ecological, organizational, and environmental impacts using different perspectives and methodologies. Simultaneously, few studies (Francoeur et al., 2019; Morgan & Rayner, 2019; Rayner & Morgan, 2018) have been giving attention to the individual level as the primary source of creating and developing new practices, especially during ecological and health crisis. Therefore, this study theoretically proposes and sets a new research model in the light of COVID-19 by discussing the new practices that must be applied and developed to face the destructive socio-economic impacts. The primary objective of this research is to analyze and establish the first relationships between green workplace environment

(GWE), employee's green behavior (EGB) to support green innovation practices (GIP), and organizational and environmental outcomes during this COVID-19 outbreak in the Algerian context. The authors examined the detailed literature and reviewed current and prior research to discuss relevant gaps and extending past studies.

2 Literature Review

Due to the increased number of employees working from home (EWFH) followed by governmental public health regulations to reduce and impede the spread of the COVID-19, green workplace environment (GWE) and employee's green behavior (EGB) take a serious place to deal with it. Firms' human resource management (FHRM) is aware of the acute effects of GWE and EGB on creating and leveraging green practices, which led to enhance organizational performance and maintain ecosystem performance (Francoeur et al., 2019; Rayner & Morgan, 2018). A systematic study by Francoeur et al. (2019) argued that the work environment plays a significant role in the motivation, capacity, and employees' opportunities to develop organizational capabilities, namely responding to ecological and societal concerns (Rayner & Morgan, 2018). Consequently, due to the global incidence of the COVID-19 and responding to the authorities' concerns to impede the spread of the COVID-19, firms are required to follow, respond, and apply a wide range of profound social and health regulations (Kraus et al., 2020a). These social and health practices mainly focus on social distancing, hand sanitizing, face masks, working from home, and reducing workers (Kim, 2020).

Rather than the consequences of these terrible moments that humanity witnessed by the global pandemic crisis, green practices that mainly emphasize cleanliness, green behavior, and ecosystem sustainability are its outcomes (Rowan & Galanakis, 2020). Entrepreneurs and professionals are giving much attention and acknowledge that these practices are in the form that fit governmental and health agencies' advice to encounter the COVID-19 pandemic (Harja, 2020; Kristinae et al., 2020). Therefore, the authors are willing to address the importance of green workplace and employee's green behavior on green practices and how this last impacts Algerian firms' organizational and environmental aspects during the COVID-19. Green et al. (2020) highlighted five key challenges to deal with COVID-19 in New Zealand: lack of management preparedness, working environment, technology infrastructure, communication, and performance outcomes and assessments. Meanwhile, another study by Badrianto and Ekhsan (2020) stated that employee's performance and job satisfaction are impacted by the work environment quality.

Green economic transition is an essential step required for all nations and economies to minimize the consequences of the COVID-19 (Elliott et al., 2020). This might empower entrepreneurial green mindsets to develop and foster businesses in light of the COVID-19 situation and restrictions (Castro & Zermeño, 2020). More particularly, to avoid further destruction of resources, ecosystem concerns, unemployment, poverty, and all social and health problems, the green transition also offers strategic opportunities to sustain the environment and natural disasters (Lin et al., 2018). The green transition allows firms to avoid waste emissions and hazards, especially those related to public health sectors, which leads to saving the environment. Additionally, green economic transition facilitates and promotes green practices that addressed environmental concerns and societal problems (Song et al., 2020). One of the main drivers that help nations green transition is developing a green workplace environment and occupier's green behavior. A firm that offers green workplace and leverage green behavior is expected to impact green economic transition and ecosystem sustainability (Silajdžić et al., 2015) by developing eco-friendly products, responding to customer environmental awareness, minimizing waste hazardous, energy-saving and consumption, production efficiencies, groundwater, and air emissions quality (Gliedt et al., 2018). Economic green transition is the main focus of the green entrepreneurial mindset (Gibbs & O'Neill, 2014).

In addition to the social and public health restrictions concerning the COVID-19, green workplace and green behavior guarantee to impede the spread of the COVID-19 by leveraging the safety and security policies such as hand sanitizing, facemask, social distancing, reconfigure workers team group, and clean production systems. This, in turn, leads to increase job satisfaction and employee performance (Shan & Tang, 2020). Organizational performance faces substantial challenges since most factories apply the working from home approach or reduce the managerial and operational capacities to limit the COVID-19. Hence, the green workplace and green employees' behavior could be seen as significant drivers that replace the strategic business policies to overcome the COVID-19 incidences. Furthermore, firms can reconfigure business operations and managerial tasks assisting the corporations in developing new capabilities to fit the new environmental business era. Past studies (Aboelmaged & Hashem, 2019; Bai et al., 2019; Kraus et al., 2020b; Nasrollahi et al., 2020) have focused on several factors that help firms deploy green practices to improve organizational performance.

Yet, few studies are trying to link the relationship between green workplace, employees green behavior, and its impact on the development of green practices (Francoeur et al., 2019), mainly in the existence of the COVID-19 pandemic. On the other hand, most of the prior studies (Albort-Morant et al., 2016; Chen et al., 2014; Kong et al., 2016; Kraus et al., 2020b) have examined antecedents and outcomes of green practices using organizational or national level (Kasayanond et al., 2019; Lin et al., 2018), while failed to cover individual level, which is the core issue that encounters the economies and entrepreneurs in light of the COVID-19. In comparison, ecosystem sustainability is highly influenced by the extent of managing to reduce hazardous waste generation and energy consumptions, alongside the practices that address societal and health restrictions to ensure business survival based on the environmental sustainability goals. Up to date, prior research (Kraus et al., 2020b; Rehman et al., 2020; Saudi et al., 2019; Singh et al., 2020) has addressed important factors that enhancing environmental performance, but most of the studies using cooperation and the national level (Amankwah-Amoah, 2020; Elliott et al., 2020). Few research highlights the core focus of individual participation and contribution to developing green practices and green behavior complexity in dealing with such a crisis as the COVID-19 pandemic led to creating vigorous debates about its importance to save firms business failure (Francoeur et al., 2019; Rayner & Morgan, 2018). Accordingly, this research intends to emphasize employees' and management's role in developing and applying appropriate practices to handle the current pandemic situation's challenges.

2.1 Linking Employees Green Behavior and Green Workplace Environment in the Context of Algerian Green Organization

Employees' green behavior (EGB) is seen as individual behavior while pursuing a particular task to contribute to ecosystem sustainability (Norton et al., 2017). This can empower firms to form a substantial force of environmental protection to deal with existing ecological concerns. Entrepreneurs and organizations are concerned about environmental issues and, thus, accept that "go for green" leads firms to prevent the environmental problems associated with COVID-19. Besides, Unsworth et al. (2013) point out that there is substantial evidence about the crucial role of individuals' green behavior in firms' success to promote ecosystem sustainability. For example, prior studies demonstrate that employee behavior significantly contributes to organizational and environmental performance (Boiral et al., 2015), cost-saving and waste reduction (Tam & Tam, 2008), and competitive advantage (Del Brío et al., 2007). Recent empirical evidence by Saeed et al. (2019) assessed green human resource management's impact on employee's pro-environmental behavior. The study findings revealed that GHRM positively influences employee behavior and employees' environmental knowledge, strengthening the relationship between GHRM and firms' pro-environmental behavior (Saeed et al., 2019).

Another study by Dumont et al. (2017) found that GHRM plays a vital role in promoting and enhancing workplace green behavior. Recently, a study by Ansari et al. (2021) empirically tested the impact of GHRM on employee's pro-environmental behavior (EPB). The research by Ansari et al. (2021) indicates that GHRM positively impacts EPB, signifying that firm's environmental awareness is able to influence individuals, society, and the economy. Safari et al. (2018) come out with the positive impact of environmental knowledge and awareness on managers' green behavior. In the context of the service industry, an empirical study by Chan et al. (2014) stated that environmental knowledge, environmental awareness, and environmental concerns are positively associated with employees' ecological behavior in hotel companies, which this last positively enable employees ecological behavior to improve green practices. An employee's willingness to develop and leverage environment friendly ideas tends to be involved by the supportive workplace environment provided by green HR practices (Saeed et al., 2019).

Ones and Dilchert (2012) called organizational researchers to examine the impact of EGB on different measures in individual, corporate, or environmental context. More particularly, studies have emphasized the need to explore the importance of EGB from multilevel perspectives (Norton et al., 2015, 2017).

In the context of organization-green orientation, the literature showed flawed studies that emphasize the closed link between employee's green behavior (EGB), green workplace environment (GWE), and organization-green orientation (OGO). However, due to the profound moments that entrepreneurs and organizations are encountered worldwide, a green workplace environment and green employee mindset are acknowledged as serious drivers to overcome environmental problems associated with the global pandemic. These green practices took a critical place to impede the high spread of COVID-19. It is imperative to note that employee's green mindset could have a significant impact on society and public health. These green practices that developed within and between organizations lead employee's green behavior to support public health management, improve ecosystem performance, and enhance green business efficiency. Employees' engagement in green behavior is expected to share and to improve society's green practices by preventing the spread of COVID-19, which would support governmental ecosystem policies. Therefore, employee's green behavior is viewed as a mechanism that enables business green practices and environmental innovation in the era of the COVID-19 epidemic.

Referring to the consequences of COVID-19 on individuals, organizations, economies, and societies that have been witnessed worldwide (Chakraborty & Maity, 2020), and given the valuable outcomes of employee's green behavior (EGB) (Saleem et al., 2021), lack of studies has been observed in the literature in dealing with the EGB antecedents and its outcomes. For example, some predetermining factors are human resource management practices (Saeed et al., 2019), eco-friendly servant leadership (Afsar & Badir, 2017), and employee's environmental knowledge and awareness (Safari et al., 2018). Managerial ecological concerns are determinants of employee's ecosystem awareness which studies have shown a significant impact of this last factor on eco-innovation and environmental performance (Meirun et al., 2020). This means that managers have valuable knowledge about ecological concerns embedded within their green behavior and attitudes. Furthermore, the present study elaborates several interrelationships that emphasize employees' green behavior, green practices, and organizational and environmental performance. However, studies on the determining outcomes of EGB are yet to be fully explored (Saeed et al., 2019), particularly in developing countries like Algeria. Hence, understanding the mechanisms by which Algerian firms can encourage EGB is incomplete and limited (Saleem et al., 2021).

To be ecologically green and safe, we need to promote, influence, and encourage employees to spread green practices. How firms can influence their employees to join, share, and leverage green behavior is crucial, especially in the global pandemic era. A recent empirical study by Junsheng et al. (2020) addressed a critical gap by testing the impact of employees' green motivation (EGM) and its relations to firms' green behavior. The study's findings found that EGM is acquiring a positive and significant effect on a firm's green behavior. In counterpart, an analysis of Ansari et al. (2021) found that firms' GHRM possess a significant impact on enabling employee's pro-environmental behavior.

Existing literature remains unclear and theoretically overlooked about the critical role of a firm's environmental practices and policies in line with the perception of EGB (Saleem et al., 2021). Besides, past studies somewhat failed to examine the intermediate link between employee satisfaction as an outlet of green behavior deployment. Accordingly, it is essential to address how EGB can impact job satisfaction and improve green practices to maintain ecosystem performance. Additionally, a lack of studies that examined the role of green behavior in promoting green workplace has been observed. Notably, most prior studies were theoretical (Norton et al., 2015; Saleem et al., 2021) and conceptually with less emphasis on empirical evidence testing the modeled path. As a result, this research hypothesizes the missed gaps by linking the interrelationships between GWE, EGB, employee satisfaction, green practices, and environmental performance from a multilevel perspective, which differs from previously existing literature.

3 Research Model, Theories, and Hypotheses Propositions

By applying the dynamic capability view (DCV) (Teece, 2016, 2018; Teece et al., 1997) and referring to the AMO theory (ability, motivation, and opportunities) (Appelbaum et al., 2000; Singh et al., 2020), the study examines the first interrelationship among constructs. It covers the study's research model to test the proposed hypotheses. By linking these two theories, it is expected to develop practices acquired by the human resource management to fit the challenging business environment and contribute to the national recovery plans by facilitating the learning processes and occupiers' environmental awareness. Authors believe that the DCV offers a guiding paradigm for better enabling the AMO theory to understand, predict, and control changes in the firm's human resources practices. Following the above discussion and referring to the detailed prior literature, the study aims to propose the following hypotheses:

Direct hypotheses:

Hypothesis 1: There is a positive association between green workplace environment and employee's green behavior.
Hypothesis 2: There is a positive association between green workplace environment and employee satisfaction.
Hypothesis 3: There is a positive association between employees' green behavior and green practices.
Hypothesis 4: Employees satisfaction positively associated with green practices.

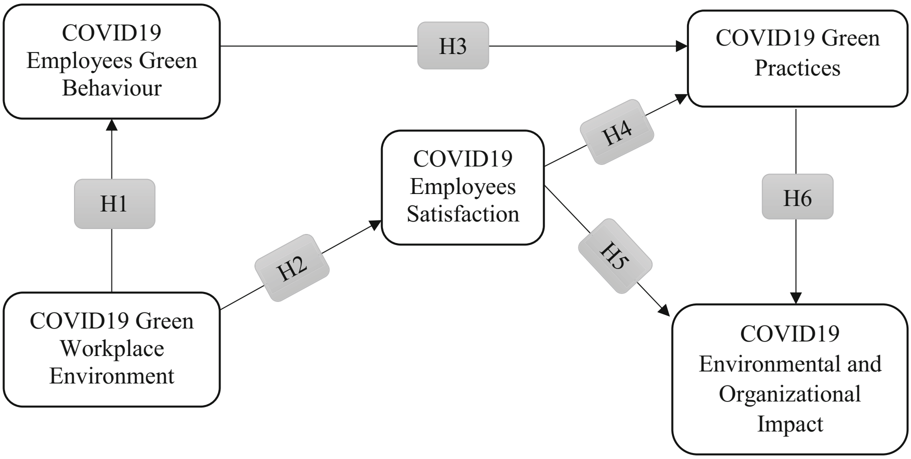

Fig. 1 Research model of the study

Hypothesis 5: Employees satisfaction positively associated with post-COVID-19 environmental impact.
Hypothesis 6: Green practices positively associated with post-COVID-19 environmental impact.

Indirect hypotheses:

H1a: Employees' green behavior positively mediates the relationship between green workplace environment and green practices.
H4a: Employees' satisfaction positively mediates the relationship between green workplace environment and green practices.
H4b: Employees' satisfaction positively mediates the relationship between green workplace environment and COVID-19 environmental impact.

Referring to the above discussions and the hypotheses propositions, Fig. 1 presents the study's research framework.

4 Implications

This chapter's outcomes possess different major propositions highlighting new relationships between green workplace environment, employee's green behavior, job satisfaction, and its implications on developing green practices and their consequences on organizational and environmental impacts during the COVID-19. This research reviewed previous studies that address separately the relationships among research model constructs and from different perspectives containing essential information and gaps of the study. The study proposes the necessary collaboration between and within various stakeholders, partners, governmental, and institutional at the global scale to reduce the spread of COVID-19 and the recovery of the economy in the soonest time. Besides, the study consists of new insights mainly discussing the importance of individual-level as the critical source to deal with the challenging period by developing green practices that act as dynamic capabilities to help firms and employees to contain heath restrictions and authorities regulations. Therefore, green practices developed by the employees' environmental awareness and management green mindset, which in turn lead to job satisfaction and increasing ecosystem performance while economies are still in the recovery stage after the global health crisis. The study suggests testing the proposed hypotheses and examines the interrelationships between variables by using different methodological and theoretical approaches in the light of COVID-19.

It is assumed that this study would help authorities and manufacturers contribute to economic recovery and public health sustainability at the country level. Algerian authorities should refer to the study research model to apply appropriate policies and procedures in dealing with the COVID-19 pandemic by giving much attention to the development and promoting the importance of green practices among firms' employees and management to fit the emergence of the COVID-19 epidemic. By linking the study model to the national strategies and governmental regulations, it is expected to acquire significant practical implications in a short and extended period, especially for those start-up entrepreneurs and firms with limited resources. Theoretically, the study helps extend the body of knowledge from the dynamic capability view and AMO theory (ability, motivation, and opportunities). Hence, the chapter proposes linking these two theories to address the hypotheses propositions and overcome the study's core issues.

5 Conclusions

The coronavirus (COVID-19) will be argued about for subsequent decades to come. It is considered as one of the current global health crises consisting of significant implications at all levels. This study explores the impact of employees and management on developing green practices to meet environmental challenges and enhance organizational performance. The study used DCV and AMO theories to overcome the issues highlighted in the research and extend the AMO lens body to understand the crucial role of an individual's contribution to organizational and environmental performance. While most current research focuses on the corporation and national level in estimating the impacts of COVID-19 from different points of view, this research gave much attention to the individual-level effects on environmental and organizational performance, arguing the critical role of occupiers in dealing with the epidemic COVID-19. It is suggested that the HRM should develop their employee's green behavior in line with restrictions and regulations related to COVID-19. By responding to the public health recommendations, the firms would continue maintaining their business survival and helping nations' economic recovery plans.

Referring to the DCV and AMO lenses, the study proposed that by fostering green workplace environment and developing green behavior, the firms might improve employees' job satisfaction. This, in turn, leads to let employees and management innovate and shift green practices to the level that the modern firms environmentally encounter serious challenges. In Algeria, the firms are still reluctant to leverage green innovation practices, and the manager's environmental awareness was not sure whether the focus of management and HRM. The study recommends Algerian entrepreneurs reconfigure dynamic business capabilities, employees' learning process, leveraging green behavior, developing a clean workplace, reconfiguring production system efficiencies, reducing energy consumptions, and promoting eco-friendly products and services. These could lead to reducing the consequences behind the epidemic COVDI-19 and save natural resources disaster. Managers and HRM should look at the implications behind the study suggestions.

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The Oil-Price Threshold Effect on External Balances in Saudi Arabia, Russia, and Canada: Accounting for Geopolitics and Environmental Sustainability

Noha A. Razek, Emilson Silva, and Nyakundi M. Michieka

1 Introduction

In 2016, OPEC members and 11 non-OPEC countries issued a Declaration of Cooperation to stabilize the global oil market through voluntary production adjustments. These countries, collectively known as OPEC+, seek to create a sustainable, stable oil market and establish a reasonable oil price that benefits all industry stakeholders and the global economy. Yet the question is, what oil price is reasonable? In this chapter, we attempt to answer this question for Saudi Arabia, Russia, and Canada. Our threshold analysis enables us to quantitatively gauge the direction of OPEC+ negotiations, led by Saudi Arabia and Russia, by identifying the price level that is reasonable to their economies and oil sectors. We also examine Canada, a non-OPEC+ high-cost producer with constrained take-away capacity.

The year 2018 was eventful for the oil market, demonstrating that the OPEC matters, and so do other non-OPEC producers. Presently, the largest producers in the market are Saudi Arabia, Russia, and the United States, followed by Canada

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The views expressed in this study are those of the authors and do not necessarily represent the views of the affiliated institution.

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(EIA, 2019). In 2019, at OPEC+ meetings led by Saudi Arabia and Russia, participants have shown commitment to the Declaration of Cooperation agreement (EIA, 2018b; Fattouh & Economou, 2018; OPEC, 2018; Razek & Michieka, 2019). However, in March 2020, the Saudi–Russian market-share war commenced amid the coronavirus severe demand shock and oil prices plunged.[1] By the end of March, Brent, West Texas Intermediate (WTI), and West Canadian Select (WCS) dropped to approximately USD 14.85/barrel, 20.51/barrel, and 5/barrel; respectively. The events were seen by analysts as a deliberate action by Saudi Arabia and Russia to squeeze out high-cost producers. However, Saudi and Russia had underestimated the severe demand shock as demand dried, storage capacity ran down and oil prices collapsed, putting the Saudi and Russian economies at stake despite being low-cost producers. By the beginning of April 2020, OPEC+ held an urgent meeting to cut production to stabilize oil prices (Sheppard et al., 2020; Watkins, 2020); yet, that decision was too late to prevent the occurrence of the low oil-price regime amid the COVID-19 shock.

When oil prices drop, oil producers immediately focus on production breakeven and fiscal breakeven. However, oil exporters' external balances come under pressure and current accounts deteriorate when oil prices drop. Although some oil exporters can finance external deficits through their external wealth, other oil exporters face pressure on their reserves. Therefore, it is important to assess oil exporters' external balances. For an economy with limited export diversification and a prominent oil sector, the current account is inextricably tied to the oil balance, creating a systematic relationship between the current account and oil prices. Managing foreign assets would enable an oil exporter to mitigate abrupt declines in oil production and exports, thereby making its economy more resilient to oil-price shocks. Fiscal and external sustainability are not perfect substitutes unless oil producers are fully owned and operated by the government[2] (Allegret et al., 2014; Arezki & Hasanov, 2013; Behar & Fouejieu, 2016; Tabeke & York, 2011; Versailles, 2015).

Despite the importance of addressing the external balance in oil producing economies, most research on oil producers has focused on fiscal sustainability and the non-oil primary fiscal balance. Few researchers have investigated the external balance for oil exporters (Akanbi & Sbia, 2018; Allegret et al., 2014; Behar & Fouejieu, 2016; Gnimassoun et al., 2017; Morsy, 2009; Tabeke & York, 2011). Research on the relationship between the current account and fiscal policy, oil prices, and/or financial development is inadequate, and most researchers have used panel data rather than country-specific data. Moreover, only Kilian et al.

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[1] In March 2020, Saudi Arabia demanded larger and longer production cuts. Moscow felt Riyadh sought to force it to agree to production cuts by either choosing to comply or to watch oil supply increase and oil prices drop. Despite the oil price dropping, Russia resisted the Saudi-led proposition to reduce production and announced quotas would expire at the end of the month, and producers were free to produce without restraint starting in April (Bordoff, 2020; McNally, 2020; Smith et al., 2020).

[2] Chalk and Hemming (2000) showed that the relationship between fiscal and external sustainability is neither 1:1 nor entirely independent.

(2009) accounted for global business cycles, and no researchers have accounted for environmental sustainability and the impact of pipeline constraints.[3]

Our objective is to assess the oil-price threshold effect on the current account to help policymakers determine the magnitude of policy adjustments needed to attain external breakeven (i.e., to finance external deficits). Building on Gnimassoun et al. (2017), we adopt a macroeconomic approach to explore the impacts of pipeline politics and geopolitics, incorporate an environmental sustainability measure, and use threshold regression analysis to account for cyclical movements. Our detailed case studies contribute to the literature on oil exporters. The direction and magnitude of the relationship between oil prices and a country's current account depend on the features of economy, the extent of domestic financial development, the level of international financial market integration, and how foreign exchange rate reserves are managed. For oil exporters, the relationship between oil prices and the current account also depends on their ability to absorb oil shocks (Gnimassoun et al., 2017). Because oil exporters are heterogeneous in terms of income and financial development, the relationships among the current account, fiscal balance, and oil prices are likely to be country-specific and influenced by the economic environment (Allegret et al., 2014).

We study Saudi Arabia and Russia because they play leading roles in OPEC+ and the global oil market. Canada is an interesting case because it has close trade links with the United States, is not a member of OPEC+, and has a more diversified oil exporting economy[4] (Gnimassoun et al., 2017). Zooming in on oil-producing provinces, Alberta, which is heavily oil dependent, faces the same economic issues as Saudi Arabia and Russia. Alberta faces pipeline politics and is landlocked, with more accentuated takeaway obstacles (as reflected in the price differentials depicted in Fig. 1); Russia has faced international sanctions and pipeline politics; and Saudi Arabia has endured recent attacks on key infrastructure, including its vital East–West pipeline, oil tankers passing through the strait of Hormuz, and Aramco facilities. Moreover, Saudi Arabia and Russia represent low-cost producers and Canada represents a high-cost producer. Canada has higher costs of production and more constrained take-away capacity than the United States (Büyükşahin et al., 2016).

Analysis could be improved, and a more detailed picture of cycle dynamics could be obtained by replacing linear time series models with nonlinear time series models (Potter, 1999). Ignoring nonlinearity can lead to policy errors with potentially serious consequences (Enders, 2015). We apply an open loop threshold autoregressive (TAR) system (Tong & Lim, 1980), to estimate the threshold oil price effect, which enables us to account for cyclical effects. To ensure robustness, we apply threshold

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[3] Silva and Razek (2016) studied the impact of pipeline constraints on wages in the oil and gas and construction sectors as well as the role of the public sector in Alberta, but did not study how such constraints affect the current account, fiscal balance and oil prices.

[4] Canada is a net oil exporter and is quite well diversified; oil accounts for less than 20% of total exports (Gnimassoun et al., 2017).

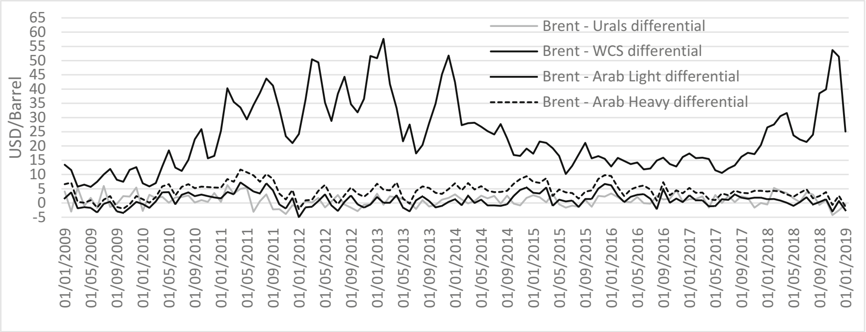

Fig. 1 Oil price differentials. (Source: EIA and Thomson Reuters)

vector autoregressive (TVAR), self-exciting threshold autoregressive (SETAR) and smooth threshold autoregressive (STAR) models, and test for strong and weak exogeneity. We account for several variables: the current account to gross domestic product (GDP) ratio; the change in net foreign assets (NFA) to GDP ratio; the fiscal balance to GDP ratio; Brent oil price; official international reserves; propensity to spend oil revenues on imports; real effective exchange rate (REER); oil price differentials and military expenditure to GDP ratio; refinery margin and capacity utilization (to capture supply-side dynamics); and a net national savings variable adjusted for expenditure on education and for environmental damage and depletion.

Our analyses show that the oil-price threshold effects on the external balance to GDP ratio are approximately USD 61–65/barrel, USD 57–58/barrel, and USD 74–76/barrel for Saudi Arabia, Russia, and Canada, respectively; i.e., it is not good news for the respective country if oil prices are within or below the stated ranges. When including the adjusted net national savings variable, the oil-price threshold effects are higher (approximately USD 72/barrel, USD 67/barrel, and USD 85/barrel for Saudi Arabia, Russia, and Canada, respectively). We are also able to identify the high and low oil-price regimes for the three economies and the reasonable oil price level for their oil sectors. The threshold for the Canadian economy and oil sector is higher, reflecting its vulnerability to oil-price shocks despite its relatively more diversified economy. Although the threshold for the oil sector is lower in Saudi Arabia than Russia, Saudi Arabia needs a higher price level than Russia to finance its international obligations.

2 Literature Review

Few researchers have investigated oil exporters' external balances (Akanbi & Sbia, 2018; Allegret et al., 2014; Behar & Fouejieu, 2016; Gnimassoun et al., 2017; Morsy, 2009; Tabeke & York, 2011). Evidence on the relationship between the current account and fiscal policy, oil prices, and/or financial development is scant, and most research is based on panel data rather than country-specific data.

Bems and de Carvalho (2009) calibrated data to study the relationship between savings and the current account in Saudi Arabia and 10 other oil exporters (not including Russia and Canada); however, they only used 2006 data. Morsy (2009), Tabeke and York (2011), Behar and Fouejieu (2016), Allegret et al. (2014), and Akanbi and Sbia (2018) applied panel data analysis to different oil exporters over different time periods. Their results emphasize the close connection between fiscal and external balances; the importance of accounting for financial development, demographics, and nonlinearity; and the fact that fiscal policy has a larger impact than exchange rate adjustments, which may be ineffective for oil exporters. They included Saudi Arabia and Russia in their samples, but did not provide details on these specific countries in their findings, opting instead to discuss the results for the entire sample. None of these researchers included Canada in their samples.

Afonso and Rault (2009) and Bluedorn and Leigh (2011) examined the relationship between the current account and the budget balance for a group of OECD countries. They discussed findings for the entire sample without providing specifics about Canada and did not study the effect of oil prices. Gnimassoun et al. (2017) focused on Canada and studied the impact of oil price movements on the current account. Their results highlight the importance of accounting for the degree of domestic financial development, the management of foreign exchange reserves and the tendency to spend oil revenues on imports. Kilian et al. (2009) studied the effects of disentangled oil-price shocks on different external balance measures for members of OPEC and Canada, but did not study Russia. Kilian (2017) studied the impact of the US shale revolution on Saudi Arabia's foreign exchange reserves; but neither applied threshold analysis nor examined the implications for Saudi Arabia's current account.

Gnimassoun et al. (2017) and Kilian et al. (2009) did not examine the impact of fiscal policy. Bems and de Carvalho (2009), Kilian et al. (2009), Morsy (2009), Tabeke and York (2011), Behar and Fouejieu (2016), Allegret et al. (2014), Gnimassoun et al. (2017), and Akanbi and Sbia (2018) studied neither the impact of pipeline bottlenecks nor the 2014 oil price episode. Only Kilian et al. (2009) examine the impact of economic cycles oil exporters' external balances; and none examined the oil price threshold effect on external balances. Setser and Frank (2017) analyzed what they called the "external breakeven." They studied a group of countries that included Saudi Arabia and Russia, but not Canada. Kleinberg et al. (2018) provided a comprehensive analysis of oil-price breakeven points for a tight oil project and discussed the fiscal breakeven, but did not examine external balances. Neither Setser and Frank (2017) nor Kleinberg et al. (2018) performed statistical modeling-based analysis. None accounted for geopolitics and environmental sustainability.

We examine the oil-price threshold effect on external balances; accounting for fiscal policy, international reserves, exchange rate, pipeline politics, and nonlinearity. We apply time series rather than panel data techniques and focus on Saudi Arabia, Russia, and Canada, thereby contributing to the literature on oil exporters. Unlike Setser and Frank (2017) who employ a simple formula, we build an economic model to conduct empirical analysis to estimate the threshold and identify the high and low oil price regimes and the effect of the determinants across regimes.

3 Methodology

3.1 The Model

Based on the theoretical background detailed in the Annex 1, we model the current account as follows:

$$\frac{\mathrm{CA}_t}{\mathrm{GDP}_t} = f\left(\frac{\mathrm{bdg}_t}{\mathrm{GDP}_t}, \mathrm{Brent}_t, \mathrm{POdiff}_t, \mathrm{REER}_t, \mathrm{imp}_t, \mathrm{RSRV}_t\right) \tag{1}$$

$\frac{\mathrm{CA}_t}{\mathrm{GDP}_t}$ is the current account to GDP ratio[5]; $\frac{\mathrm{bdg}_\mathrm{t}}{\mathrm{GDP}_t}$ is the fiscal balance to GDP ratio; Brent_t is the Brent nominal oil price; POdiff_t is the oil price differential; REER_t is the real effective exchange rate; imp_t is the propensity to spend oil revenues on imports; and RSRV_t is the value of official international reserves. We also use the change in NFA to GDP ratio ($\frac{\Delta\mathrm{NFA}_t}{\mathrm{GDP}_t}$) instead of $\frac{\mathrm{CA}_t}{\mathrm{GDP}_t}$.

To account for the fiscal policy effect, we use the overall and primary fiscal balance to GDP ratio. We use the Brent oil price to examine the impact of oil price on relationships between variables in a global context. In 2018, the increase in the US production coupled with takeaway capacity constraints led to an increase in the Brent-WTI spread (Fig. 2). Therefore, we use Brent rather than WTI oil price as the threshold variable. Figure 3 shows that the difference between the nominal and real Brent oil price is small. Hence, we use the nominal oil price in the model. To model the role of pipeline politics and geopolitics and capture the impact of takeaway capacity, we employ oil price differentials. The graphical analysis in Fig. 1 depicts the Brent-WCS (Canada), Brent-Urals blend (Russia),[6] Brent-Arab Light (Saudi), and Brent-Arab Heavy (Saudi) oil price differentials, which show that the impact of pipeline politics is more pronounced in Canada.

REER is an inflation-adjusted measure and a better indicator of competitiveness than the nominal effective exchange rate (NEER) because the former captures price differentials between a country and its trade partners. A decrease in REER indicates real depreciation of the Saudi, Canadian, and Russian currencies. It is important to note that we use the REER, not the bilateral exchange rate. Similar to Tabeke and

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[5] We use this ratio to examine and compare countries over time.

[6] Russia exports crude oil through five main pipelines. Nearly 90% of exports are handled by Transneft, the national oil pipeline operator (Institute of Energy for South-East Europe, n.d.) which transports oil directly to neighboring countries or to ports, where more than 80% of crude oil and condensate exports are shipped by sea. Smaller volumes of exports are shipped by rail or vessels loaded at independently owned terminals (EIA, 2017).

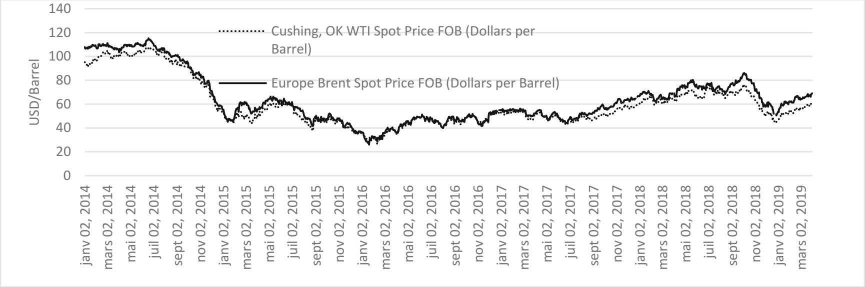

Fig. 2 Nominal Brent and WTI spot oil prices (Jan 1, 2014 to Apr 1, 2019). (Source: EIA)

Fig. 3 Real and nominal Brent oil price (1997M01 to 2018M06). (Source: EIA and OECD Main Economic Indicators)

York (2011) and Behar and Fouejieu (2016), we account for REER in the model; however, identifying the optimal exchange rate or the appropriate exchange rate regime is beyond the scope of this study.[7]

Following Gnimassoun et al. (2017), we employ the ratio of import expenditures to oil export revenues to study the propensity to spend surplus oil revenues on imports; moreover, we utilize the value of official international reserves to capture a country's capacity to manage exchange rate reserves. According to Rebucci and Spatafora (2006) and Kilian et al. (2009), a tendency to spend oil revenues on imports would decrease pass-through effects of oil demand shocks. A monetary authority may acquire foreign exchange reserves after a sudden increase in oil revenue to alleviate currency appreciation, thereby limiting an increase in domestic

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[7] Canada follows a flexible exchange rate regime and Saudi Arabia follows a fixed exchange rate regime. In November 2014, the Bank of Russia switched from a managed floating exchange rate regime to a floating exchange rate regime (Vlasov & Deryugina, 2018). We intend to contribute neither to the debate on fixed versus flexible exchange rate regimes nor to the discussion on the appropriate choice of exchange rate regime. It is important to note that the dollar peg regime has been advantageous to the Saudi economy and will continue to be so until Saudi Arabia's exports are denominated in a mixture of currencies and the economy is diversified (Alkhareif et al., 2017).

prices that would decrease exporters' competitiveness and lead to an increase in imports. By managing foreign exchange reserves, a country can control deficits in the non-oil trade balance, hence augmenting the ultimate positive effect of a rise in oil price on the current account (Gnimassoun et al., 2017). Fatum et al. (2016) explained that oil-rich countries with low productivity are more susceptible to oil shocks and hence accumulate international reserves as precautionary savings and a buffer against oil-price shocks to smooth aggregate consumption.

3.2 Empirical Methodology: Threshold Regression

3.2.1 Why Employ a TAR Model?

Tong and Lim (1980) emphasized the utility of nonlinear time series models (and the inadequacy of linear models) for analyzing cyclical movements, highlighting that TAR models based on piece-wise linearization are in general enough to capture cyclicality. Nonlinear time series models yield more accurate estimates and enable a more nuanced understanding of cyclical dynamics than linear time series models (Potter, 1999). If nonlinearity is ignored, policies could be based on seriously flawed inputs. However, caution must be exercised, as using an incorrect nonlinear specification may have more serious consequences than ignoring nonlinearity in the first place (Enders, 2015).

Among nonlinear models, the three main types are TAR,[8] smooth transition autoregressive (STAR), and Markov switching. The past values of time series define the regimes of the first two types of models (i.e., threshold variables are observable), whereas the exogenous state of the Markov chain defines a Markov switching regime (i.e., the threshold variable is unobservable) (Potter, 1999). A TAR model in which the threshold variable is the lagged value of the dependent variable is referred to as a self-exciting TAR (SETAR) model (Tong, 1983). If the binary indicator function which determines the regime in a SETAR model is replaced by a smooth transition function, the model becomes a STAR model (Enders, 2015; Zivot & Wang, 2006).

Note that we are interested in determining the oil-price threshold effect(s) on the current account (i.e., we use oil price as the threshold variable). Thus, we neither use the Markov switching approach nor a SETAR model. Moreover, we do not apply a STAR model, because oil-price shocks tend to have abrupt, rather than smooth effects.[9] For instance, in 2008, oil prices dropped from approximately USD

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[8] According to Potter (1999), Bayesian techniques for the marginal inference of coefficients differ significantly from the classical approach. Specifically, intercepts are inferred in the Bayesian case by using the posterior probability of the threshold interval to weight the individual normal distributions, meaning that uncertainty about the threshold would impact the inferred coefficients. Hence, we use the classical approach.

[9] During initial analysis, we considered STAR, SETAR, and Markov switching. The results show that TAR is most appropriate.

143/barrel in July 2008 to approximately USD 39/barrel by the end of the year; in 2014, oil prices dropped from around USD 115/barrel in June 2014 to around USD 45/barrel in January 2015; and when Saudi Aramco was attacked on September 14, 2019, the Brent oil price increased from approximately USD 60–61/barrel on September 12–13 to around USD 68/barrel on September 16 before the effect of the attack faded away due to ample supply in the market. Moreover, before changes in oil production occur, precautionary demand and uncertainty surrounding future market conditions and oil supply immediately impact oil prices (Kilian, 2009). That is also why we do not include oil production in the model. Furthermore, strong and weak exogeneity and Granger causality tests demonstrate that it is more appropriate to employ TAR rather than the threshold vector autoregressive (TVAR) approach.[10] Because oil exporters are heterogeneous, relationships among the current account, monetary policy, fiscal policy, and oil prices are likely to be influenced by the country's economic conditions (Allegret et al., 2014); hence, we use time series data rather than panel data to perform a detailed analysis of each country.[11]

In our model, the dependent variable is the current account to GDP ratio (or an equivalent measure), and the explanatory variables are a combination of the explanatory variable of interest stated in Eq. (1) and the lagged value of the dependent variable. We apply a TAR-distributed lagged model in which the oil price variable is both a regressor and the threshold variable. This threshold regression is referred to by Tong and Lim (1980) as an open loop TAR system.

3.2.2 Estimation of a TAR Model

Linear regression can be extended through threshold regression to allow different regimes to have different coefficients. The value of the threshold variable determines the regime, and multiple regimes (i.e., threshold values) may be included in a single model. When analyzing macroeconomic time series, these models effectively capture unexpected breaks or asymmetries in data during an economic cycle. Using a threshold value θ , a two-regime threshold regression can be defined without loss of generality as follows:

$$\begin{aligned} y_t &= C + x_t\beta + z_t\alpha_1 + \varepsilon_t \quad \text{if} \quad \omega_{t-d} \leq \theta \\ y_t &= C + x_t\beta + z_t\alpha_2 + \varepsilon_t \quad \text{if} \quad \theta < \omega_{t-d} \end{aligned} \tag{2}$$

where y_t is the dependent variable; x_t is a $1xk$ vector of regressors; β is a $kx1$ vector of regime invariant parameters; ε_t is normally distributed error with mean 0 and variance σ^2; z_t is a vector of explanatory variables with regime-specific coefficients α_1 and α_2; ω_t is an observable threshold variable that may be one of the variables in

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[10] Results are available upon request from the authors.

[11] Note that we apply a time series not a calibration model; hence, our analysis is not driven by assumptions.

x_t or z_t (but not necessarily so) and must be predetermined relative to ε_t; and d is the delay parameter. Regime 1 is the subset of observations where $\omega_t < \theta$, and regime 2 is the subset of observations where $\omega_t > \theta$ (Bai & Perron, 2003; Enders, 2015; Potter, 1999; Stata, 2019). Because it may take the regime more than one period to switch, the timing of the regime switch is based on the value ω_{t-d} where $d = 1, 2, \ldots$ (Enders, 2015). C is a $kx1$ vector of constant terms (Tong & Lim, 1980).

The parameters of interest are α_1 and α_2. In a partial threshold model, variables that do not change across regimes are included in x_t, where β is estimated for the entire sample. A pure threshold model does not include $x_t\beta$, and all coefficients may change. Moreover, the variance of ε_t may differ across regimes, as long as breaks occur on the same dates as breaks in the regression parameters (Bai & Perron, 2003), meaning each regime's ε_t is independent (Tong & Lim, 1980). Although each regime's y_t is linear, the entire y_t sequence is nonlinear (Enders, 2015).

We allow the variables to vary across regimes, and we do not fix the variance across regimes. Hence, we examine two cases: when the variance is the same across regimes, and when it differs. Also, in light of the breakpoint unit root test results, we include dummy variables when necessary. Accordingly, the variables of interest that are summarized in Eq. (1) are reflected in z_t and the dummy variables (if included) are represented by x_t. We also include seasonal dummy variables which are included in x_t. Stigler (2012) argued against excluding the influential threshold variable from the list of regressors. Following this argument, the oil price variable (i.e., the threshold variable) is also included as a regressor.

Due to its nonstandard asymptotic distribution, inferring the nuisance parameter θ is a complex task. Because the lag length, threshold value and associated delay value are unknown, the sum of squared residuals (SSR) function cannot be differentiated with respect to those parameters. Least squares estimation can be repeated for each discrete parameter value (i.e., threshold and delay values and order of autoregressive lags). Conditional least squares can be used to estimate threshold regression parameters, and the estimated threshold value is the one associated with the minimum SSR obtained for all tentative thresholds; where the minimum SSR is derived from the following least squares regression with T observations and two regimes:

$$y_t = x_t\beta + z_t\alpha_1 I\left(\omega_t \leq \theta\right) + z_t\alpha_2 I\left(\theta < \omega_t\right) + \varepsilon_t \tag{3}$$

for a succession of T_1 values of the threshold variable ω_t. The default trimming percentage is 15%, which means that T_1 includes observations between the 15th and the 85th percentiles[12] of ω_t (i.e, $T_1 < T$). The threshold estimator is $\hat{\theta} = \arg\min_{\theta\epsilon\tau} S_{T_1}\left(\theta, \beta, \alpha\right)$, where $\tau = \left(\theta_0, \theta_{m+1}\right)$, and

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[12] The top and bottom 15% of values are excluded to ensure an adequate number of observations in each regime (Enders, 2015).

$$S_{T_1}(\theta, \beta, \alpha) = \sum_{t=1}^{T} \{y_t - C - x_t\beta - z_t\alpha_1 I(\omega_t \le \theta) - z_t\alpha_2 I(\theta < \omega_t)\}^2 \tag{4}$$

where S_{T_1} is a T_1x1 vector of SSR, and θ is a T_1x1 vector of tentative threshold values. Threshold regression estimates are obtained by minimizing $S_{T_1}(\theta, \beta, \alpha)$ with respect to the parameters through all potential regimes (Enders, 2015; Hansen, 1997; Potter, 1999; Startz, 2019; Stata, 2019).

In general, a threshold regression model with m thresholds has $m + 1$ regimes. Let $j = 1, \ldots, m + 1$ represent an index of potential threshold values. We can write the model as:

$$y_t = C + x_t\beta + z_t\alpha_1 I_1(\theta_1, \omega_t) + \cdots + z_t\alpha_{m+1} I_{m+1}(\theta_{m+1}, \omega_t) + \varepsilon_t \tag{5}$$

$$y_t = C + x_t\beta + \sum_{j=1}^{m+1} z_t\alpha_j I_j\left(\theta_j, \omega_t\right) + \varepsilon_t \tag{5$'$}$$

Using ordered threshold variable values ($\theta_1 < \theta_2 < \ldots < \theta_m$), we estimate the thresholds sequentially, where $\theta_1^*, \ldots, \theta_m^*$ represents the order of estimation for m thresholds, to obtain T consistent thresholds (Gonzalo & Pitarakis, 2002). Assuming a model with two breaks, after estimating the first threshold θ_1^*, the second threshold θ_2^* is estimated over the remaining threshold variable observations after excluding the first break, where $\hat{\theta}_2^* = \arg\min_{\theta_2^* \epsilon \tau_2} S_{T_2}\left(\theta_2^* | \hat{\theta}_1^*\right)$ and $T_2 < T_1$. Generally speaking, the mth threshold minimizes the SSR conditional on the $m - 1$ estimated thresholds, and is given by.

$\hat{\theta}_l^* = \arg\min_{\theta_l^* \epsilon \tau_l} S_{T_l}\left(\theta_l^* | \hat{\theta}_1^*, \ldots, \hat{\theta}_{l-1}^*\right)$, where $\tau_l = (\theta_0, \theta_{m+1})$ excluding $\hat{\theta}_1^*, \ldots, \hat{\theta}_{l-1}^*$. Overall, we estimate the threshold values sequentially by calculating an initial threshold value that minimizes the SSR, then use this initial threshold to search for additional values that minimize the SSR until the appropriate number of thresholds is reached, as determined by the Bai-Perron test (Bai & Perron, 1998, 2003; Stata, 2019).

The interval with the smallest SSR includes the obvious least squares estimate; any estimate within this interval is equally valid, as is the maximum likelihood estimate, assuming errors are Gaussian. Because threshold (and delay) estimates converge at a sufficiently fast rate (Chan, 1993), it is possible to ignore sampling variability in the asymptotic inference of other parameters conditioned on the least squares/maximum likelihood estimate of the threshold (Potter, 1999). Regardless of whether residual variances are restricted such that they are equal, OLS analysis yields consistent estimates of the intercept and slope coefficients, conditional on the threshold being correct (Enders, 2015); moreover, the regression that includes the smallest SSR contains the consistent threshold estimate.

To determine the lag lengths of variables included in each regime, t-tests can be performed on the individual coefficients, F-tests can be performed on groups of coefficients, and the Akaike information criterion (AIC) and/or Bayesian information criterion (BIC) can be used (Enders, 2015). According to Enders (2015), the TAR model can be estimated for each potential value of d to determine the delay parameter; the model with the smallest SSR yields the most consistent estimate. Alternatively, the delay parameter associated with the smallest value of AIC or BIC can be chosen. The second approach is useful when the appropriate lag length values in different regimes depend on d. When the number of thresholds is not known at the outset, the optimal number of thresholds is determined based on the AIC, BIC, or Hannan Quinn information criterion (HQIC), which are derived using the estimated SSR from the fitted model, where $\text{AIC} = T \ln\left(\frac{\text{SSR}}{T}\right) + 2k$, $\text{BIC} = T \ln\left(\frac{\text{SSR}}{T}\right) + k \ \ln(T)$, $\text{HQIC} = T \ln\left(\frac{\text{SSR}}{T}\right) + 2k \ \ln(\ln(T))$, and k is the number of parameters in the model (Stata, 2019). It is important to note that, according to Tong and Lim (1980), a reasonable lag length of the model is influenced by the number of parameters required for the TAR.

3.3 Data

In light of Eq. (1), the selection of the variables for each country is influenced by features of each country's economy, which in turn dictates the data availability and frequency, and hence the characteristics of and relationships between those variables. The variables used in the analysis for each of the three countries are illustrated in Figs. 4, 5 and 6.

For Saudi Arabia, available data are mainly annual. However, annual data for the propensity to spend oil revenues on imports,[13] official international reserves and Arab (Saudi) light oil price are only available starting in 1988, 1997, and 2003, respectively. Hence, we do not include the former two,[14] and replace the latter with Fateh oil price when calculating the oil price differential. We analyze annual data between 1980[15] and 2018 and account for a structural break in 1986 (SB86).

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[13] The propensity to spend oil revenues on imports is calculated as the ratio of the value of imports of goods and services to the value of GDP generated by the oil sector for Saudi Arabia. Note that the Saudi data for oil exports, GDP generated by the oil sector, and imports of goods and services are available starting in 2005, 1985, and 1988, respectively (no quarterly data are available). Calculations based on data from Oxford Economics and SAMA show that between 2005 and 2018, exports accounted for 70% to 87% of total Saudi oil production. Hence, we use oil production as the denominator.

[14] Given the relationship between REER and reserves under a fixed exchange rate regime, it is sufficient to include REER in the analysis.

[15] The Saudi REER variable is available starting in 1980.

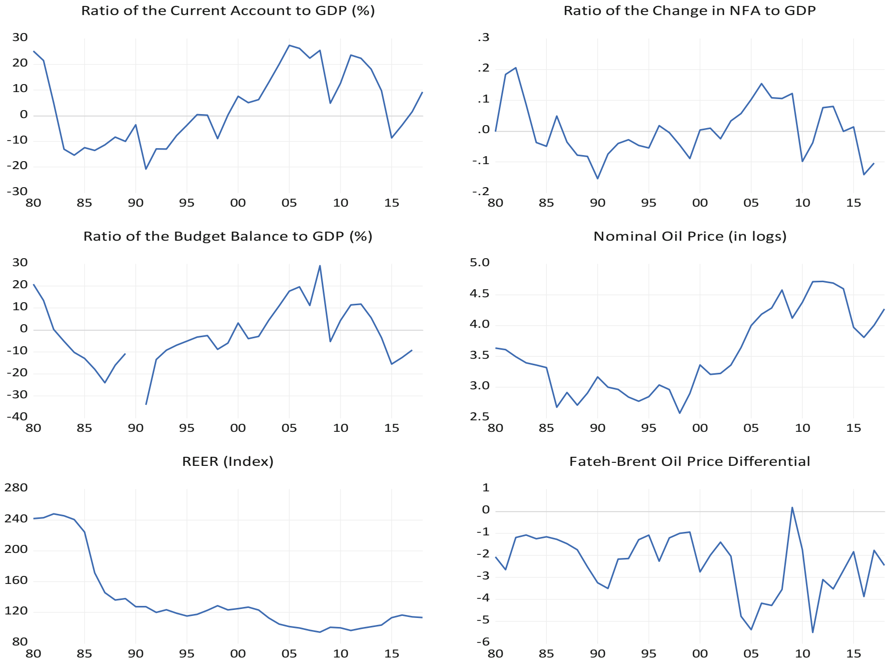

Fig. 4 Saudi Arabia (1980–2018). (Source: SAMA, IMF, World Development Indicators, Oxford Economics, OECD Annual National Accounts, and Thomson Reuters, and The Department of Energy (United Kingdom). The base year for the REER variable is 2010)

This is appropriate, because the global exchange rate regimes were different prior to the collapse of the Bretton Woods system. The global oil and foreign currency markets experienced major changes during the 1980s. Starting in 1985, Saudi Arabia changed the oil pricing mechanism, and 1986 signifies a structural break in the oil market (Griffin & Neilson, 1994; Peersman & Robays, 2009). Following the Plaza agreement in 1985, the Group of Five (G5) countries engaged in a coordinated sale of US dollars, resulting in an average 35% decrease in the value of the dollar against major foreign currencies by 1987 (Mishkin, 1997). Moreover, the SAR has been pegged to the US dollar since 1986 (Alkhareif et al., 2017). We also consider a structural break in 2000 (SB00) to account for the increase in crude price after the 1997–1998 financial crises in East Asia, Latin America, and Eastern Europe (US Federal Reserve, n.d.) and include a dummy variable in 2015 (DV15) to capture the adverse oil-price shock.

For Russia, we study the period 2002Q1 to 2019Q1 when Russia became an emerging energy power (Hill, 2002). Poussenkova (2010) explained that during the economic crisis of the 1990s, the Russian oil industry was struggling to survive. International expansion did not become a priority until the 2000s, as both crude production and oil prices increased. In an attempt to regain Russia's status as a world

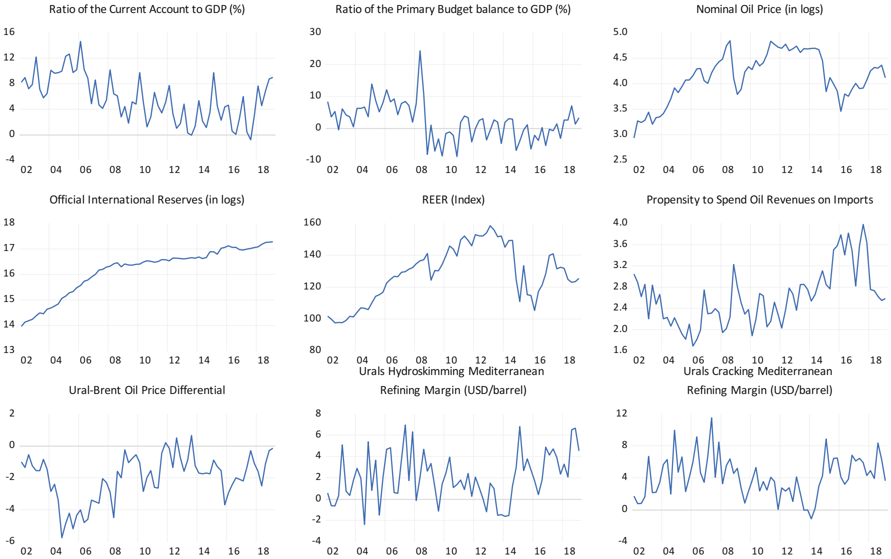

Fig. 5 Russia (2002Q1 to 2019Q1). (Source: Central Bank of Russia; Federal State Statistics Service, Russia; Ministry of Finance of the Russian Federation; IMF; Oxford Economics; EIA; and Thomson Reuters. The propensity to spend oil revenues on imports is calculated as the ratio of the value of imports of goods and services to the value of oil exports for Russia)

power, the government reestablished state control over the oil and gas industry based on the belief that economic strength and geopolitical influence is largely determined by a country's role in global energy markets.

Violence erupted in February 2014 during the crisis with Ukraine. The United States first imposed sanctions on Russia in March 2014; joint sanctions were soon imposed by the USA and key allies, including the European Union and Canada. The sanctions imposed by the United States and Canada are open-ended, but those imposed by the European Union are renewed yearly or every 6 months; in September 2019, they were imposed for another 6 months (US Department of State, n.d.). Hence, we include a structural break in 2014Q1 (SB14Q1) to account for the impact of Western sanctions and pipeline politics when modeling the Russian case. In addition to accounting for the impact of sanctions, we include a transitory shock dummy variable equal to 1 in 2008Q4 and −1 in 2009Q1 (BLP08Q49Q1) to account for the impact of the financial crisis and associated drop in oil prices.

Our analysis for Canada begins in 2005.[16] In June 2005, the US Congress approved the *Energy Policy Act of 2005*, which stimulated investment in the energy sector and large-scale shale gas extraction, causing oil and gas output to increase by

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[16] The WCS data start in 2005.

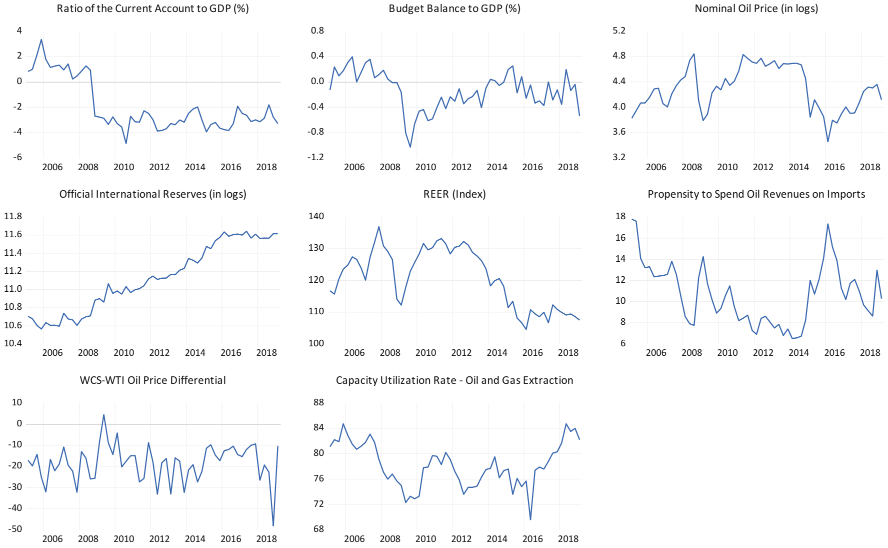

Fig. 6 Canada (2005Q1–2019Q1). (Source: Oxford Economics, CANSIM/Statistics Canada, Department of Finance Canada, IMF, EIA, Eikon/Thomson Reuters, and the Government of Alberta. The propensity to spend oil revenues on imports is calculated as the ratio of the value of imports of goods and services to the value of crude oil and crude bitumen exports for Canada. The base year for the REER index is 1999)

almost 40% between 2006 and 2013 (England & Mittal, 2014). That was associated with a surge in crude oil production in North America.[17] Silva and Razek (2016) found that this *Energy Policy Act* may have resulted in an increase in real and nominal wages in Alberta's construction and oil and gas sectors and consumer price index, reflecting Canada's close economic ties with the United States. Razek (2017) discussed links between the increase in oil prices that coincided with the *Energy Policy Act* in June 2005 and increases in Alberta's employment, retail trade, and sales of manufactured goods, and in Canada's crude oil and bitumen exports. From 2005 to 2014, growth in Canadian oil production exceeded 50% due to technological advances and increasing oil prices, which resulted in an 80% increase in crude exports and a 58% increase in pipeline deliveries; it is also observed that the Canadian energy sector reached a turning point in 2008 (McKeown et al., 2016). Hence, for Canada, we study the period 2005Q1 to 2019Q1 and include a structural break in 2008Q3 (SB0803) to account for the financial crisis and the associated drop in global economic activity and collapse in oil prices. We also include a dummy

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[17] The focus of this chapter is Canada not the USA. Graphical analyses for Canada were conducted by Silva and Razek (2016) and Razek (2017). This surge in US production is documented in EIA (n.d.-a).

variable in 2015Q1 (DV15Q1) when oil prices dropped below USD 50/barrel and the long-lasting low oil-price regime commenced. For the Canadian oil price differential variable, we use the WCS and WTI differential, because royalties in Alberta are calculated based on the Canadian dollar equivalent of the WTI oil price, and WCS is exported to the international market from the Gulf Coast.

The breakpoint unit root test and graphical analysis were applied to verify the inclusion of the aforementioned structural breaks and dummy variables. Results of the correlation analysis suggested no multicollinearity concerns,[18] and additional analyses were conducted to ensure that the models presented hereafter pass all diagnostic tests. Following the approach suggested by Enders (2015), we verified the nonlinearity of each series by conducting the Brock–Dechert–Scheinkman (BDS) test (Broock et al., 1996), which uses a general alternative hypothesis to detect serial correlation, parameter instability, neglected nonlinearity, and structural breaks. We also conducted unit root tests. Together with the graphical analyses presented in Figs. 4, 5 and 6, the BDS and unit root test results reported in Tables 1, 2, 3 and 4 suggest that the variables are I(1) and provide evidence of nonlinearity and the need for an approach to analyze the nonlinear relationship between the variables of interest.

4 Results and Robustness Checks

Each country has its economic characteristics and reports data differently. Thus, we do not build the exact same model for the three countries, and we devote different subsections for each. All models presented hereafter pass all diagnostic tests for robustness: the residuals are normally distributed and not serially autocorrelated; there is no evidence of heteroskedasticity, autoregressive conditional heteroscedasticity (ARCH), or model misspecification; and the Wald test confirms the number of regimes and rejects the restrictive model of zero breaks.

4.1 Saudi Arabia

In Table 5, we present several models that reveal the relationship between the ratio of the current account to GDP and the change in NFA to GDP on the one hand and the ratio of the budget balance to GDP, REER, Brent, and the oil price differential on the other hand. The dependent variables in Models 1, 2, and 3 are the change in NFA to GDP, current account to GDP, and budget balance to GDP, respectively.

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[18] The breakpoint unit root test and correlation analysis results are available from the authors upon request.

Table 1 BDS test (bootstrap probabilities)

		p-value							
Country	Dimensions	Current account to GDP ratio	Change in NFA to GDP ratio	Brentct	Reserves	Oil price differential	Propensity to spend oil revenues on imports	REER	Budget balance to GDP ratio
Saudi Arabia	2	***0.0000******	***0.0014******	***0.0000******	–	***0.0348*****	–	***0.0000******	***0.0200*****
Russia	2	***0.0000******	–	***0.0000******	***0.0000******	***0.0000******	***0.0000******	***0.0000******	***0.0160*****
	3	***0.0000******	–	***0.0000******	***0.0000******	***0.0000******	***0.0000******	***0.0000******	***0.0000******
	4	***0.0000******	–	***0.0000******	***0.0000******	***0.0000******	***0.0000******	***0.0000******	***0.0000******
Canada	2	***0.0000******	–	***0.0000******	***0.0000******	0.3840	***0.0000******	***0.0000******	***0.0000******
	3	***0.0000******	–	***0.0000******	***0.0000******	***0.0080******	***0.0000******	***0.0000******	***0.0000******
	4	***0.0000******	–	***0.0000******	***0.0000******	0.1120	***0.0000******	***0.0000******	***0.0000******

Source: Authors' calculations. The BDS does not perform well with regard to small samples unless the critical values are bootstrapped (Enders, 2015). For Saudi Arabia, the change in NFA to GDP ratio is 1980–2017; the time sample for other reported results is 1980–2017/2018; and the Brent oil price is a log value. For Russia, results are reported for seasonally adjusted variables; Brent oil price and reserves are log values, and the time sample is 2002Q1 to 2019Q1. For Canada, the results are reported for seasonally adjusted variables; Brent oil price and reserves are log values, and the time sample is 2005Q1 to 2019Q1

The null hypothesis indicates the series is linear. Values in bold italics indicate rejection of the null hypothesis

* $p < 0.05$

** $p < 0.01$

Table 2 Unit root tests: Saudi Arabia

Test	Null hypothesis			CA_t	ΔNFA_t	Bdg_t	$Brent_t$	$REER_t$	$POdiff_t$	ΔCA_t	$\Delta^2 NFA_t$	ΔBdg_t	$\Delta Brent_t$	$\Delta REER_t$	$\Delta POdiff_t$
ADF	Null hypothesis: unit root	RW without a drift	$Z(t)$	***−1.9198****	***−4.2109******	***−3.2037******	−0.3214	−2.7845***	−1.5606	***−5.5114******	**–**	**–**	***−5.5890******	***−3.0699******	***−6.6455******
		RW with a drift	$Z(t)$	−1.9629	***−4.1742******	***−3.1612*****	−1.2610	***−2.6233****	***−3.7159******	***−5.4379******	**–**	**–**	***−5.5470******	***−3.2440*****	**–**
		RW with an unrestricted constant, time trend in regression	$Z(t)$	−2.3248	***−3.9613*****	−3.1648	−2.0699	−1.1244	***−4.0920*****	***−5.3537******	**–**	***−6.9547******	***−5.4587******	***−3.6718*****	**–**
GLS	Null hypothesis: unit root	Test statistic		−2.2069	***−3.9870******	−2.3980	−1.9931	−2.0084	***−4.1632******	***−4.9976******	**–**	***−6.9784******	***−5.6068******	***−3.5699*****	**–**
		Minimum SIC		0	***1***	0	0	1	***0***	***0***	**–**	***0***	***0***	***0***	**–**
PP	Null hypothesis: unit root	RW with a constant and without a time trend	$Z(t)$	−2.0166	***−3.4618*****	−3.1844**	−1.2610	−2.6233*	***−3.759******	***−5.5139******	**–**	***−7.3845******	***−5.5117******	***−3.2145*****	**–**
		RW with an unrestricted constant, time trend in regression	$Z(t)$	−2.1806	***−3.5179****	−3.1840	−2.0699	−1.1244	***−4.1434*****	***−5.4308******	**–**	***−7.2177******	***−5.4158******	***−3.3288****	**–**

KPSS	Null hypothesis: level stationary	With a constant	LM-statistic	***0.3685*****	***0.1140******	***0.2379******	***0.4858******	***0.5439******	***0.3802******	***0.1288******	–	–	***0.0919******	***0.3201******	–
	Null hypothesis: trend stationary	With a constant and a linear trend	LM-statistic	***0.1141******	***0.1188******	***0.1140******	***0.1376******	***0.1604******	***0.0627******	***0.1136******	–	–	***0.0726******	***0.0880******	–

The time sample for the results is 1980–2018. An augmented Dickey–Fuller test is represented by: $\Delta y_t = \alpha + \beta y_t + \delta t + \gamma_1 \Delta y_{t-1} + \gamma_2 \Delta y_{t-2} + \cdots + \gamma_k \Delta y_{t-k} + \varepsilon_t$, where t is the time trend and α is a constant. “With a constant and without a time trend” refers the case of a random walk without a drift (i.e., α is included). “With a constant, time trend not in regression” refers to the case of a random walk with a drift that excludes the time trend. “Unrestricted constant, time trend in regression” refers to the case when y_t follows a random walk with or without a drift; i.e., α is unrestricted and t is included (Stata, 2019). Brent oil price values are in log. The time sample for the change in NFA to GDP ratio is 1980–2017. For the budget balance to GDP ratio variable, the observation for the year 1990 is missing. Values in bold italics indicate stationary variables. *ADF* augmented Dickey–Fuller, *GLS* generalized least squares, *PP* Phillips–Perron, *KPSS* Kwiatkowski, Phillips, Schmidt, and Shin, *RW* random walk

$^{*}p < 0.10$
$^{**}p < 0.05$
$^{***}p < 0.01$

Table 3 Unit root tests: Russia

Test	Null hypothesis			CA_t	Bdg_t	Brent_t	REER_t	POdiff_t	RSRV_t	Imp_t	ΔCA_t	ΔBdg_t	ΔBrent_t	ΔREER_t	ΔPOdiff_t	ΔRSRV_t	ΔImp_t
ADF	Null hypothesis: unit root	RW without a drift	$Z(t)$	−0.8761	$\boldsymbol{-1.9886}^{**}$	−0.4180	0.1998	−1.4638	3.3140	−0.7218	$\boldsymbol{-4.4990}^{***}$	–	$\boldsymbol{-7.1539}^{***}$	$\boldsymbol{-9.1380}^{***}$	$\boldsymbol{-7.2398}^{***}$	$\boldsymbol{-7.1978}^{***}$	$\boldsymbol{-8.5768}^{***}$
		RW with a drift	$Z(t)$	−1.6798	−2.1854	−2.1028	−1.9020	$\boldsymbol{-3.5424}^{***}$	0.6152	−2.4879	$\boldsymbol{-4.4289}^{***}$	$\boldsymbol{-10.1607}^{***}$	$\boldsymbol{-7.1168}^{***}$	$\boldsymbol{-9.1069}^{***}$	$\boldsymbol{-7.1806}^{***}$	$\boldsymbol{-8.3970}^{***}$	$\boldsymbol{-8.5219}$
		RW with an unrestricted constant, time trend in regression	$Z(t)$	−2.3452	−2.5295	−1.8523	−1.5817	$\boldsymbol{-3.9486}^{**}$	−2.2067	$\boldsymbol{-3.5170}^{**}$	$\boldsymbol{-5.2470}^{***}$	$\boldsymbol{-10.1163}^{***}$	$\boldsymbol{-7.1505}^{***}$	$\boldsymbol{-9.2402}^{***}$	–	$\boldsymbol{-8.4802}^{***}$	–
GLS	Null hypothesis: unit root	Test statistic		−1.7995	−2.4042	−1.6784	−1.5328	$\boldsymbol{-3.5078}^{**}$	−2.1865	−2.1245	$\boldsymbol{-3.4621}^{**}$	$\boldsymbol{-4.0645}^{***}$	$\boldsymbol{-7.1374}^{***}$	$\boldsymbol{-8.9428}^{***}$	–	$\boldsymbol{-8.6033}^{***}$	$\boldsymbol{-8.1653}^{***}$
		Minimum SIC		8	***4***	0	0	0	***0***	***0***	***3***	***3***	***0***	***0***	–	***0***	***0***
PP	Null hypothesis: unit root	RW with a constant, without a time trend	$Z(t)$	$\boldsymbol{-3.8823}^{***}$	$\boldsymbol{-4.6682}^{***}$	−2.1857	−1.8630	$\boldsymbol{-3.4000}^{**}$	0.6190	−2.5580	–	–	$\boldsymbol{-7.0169}^{***}$	$\boldsymbol{-9.0967}^{***}$	–	$\boldsymbol{-8.3987}^{***}$	$\boldsymbol{-8.9079}^{***}$

		RW with unrestricted constant, time trend in regression	$Z(t)$	***−4.7788******	***−5.4024******	−1.9675	−1.5039	***−3.7927*****	−2.5470	***−3.5300*****	–	–	***−7.0689******	***−9.2886******	–	***−8.4784******	–
KPSS	Null hypothesis: level stationary	With a constant	LM-statistic	0.7446	***0.5760******	***0.3523******	***0.4735******	0.3187***	1.0694	***0.5722******	***0.2264******	***0.1500******	***0.1569******	***0.2131******	–	***0.1342******	***0.2358******
	Null hypothesis: trend stationary	With a constant and a linear trend	LM-statistic	***0.1626******	***0.1134******	***0.2077******	0.2313	***0.0993******	***0.0896******	***0.1605******	***0.1757******	–	***0.0508******	***0.0498******	–	–	***0.1177******

Results are reported for seasonally adjusted variables. The Brent oil price and reserves are in logs. The time sample is 2002Q1 to 2019Q1. Values in bold italics indicate stationary variables. *ADF* augmented Dickey–Fuller, *GLS* generalized least squares, *PP* Phillips–Perron, *KPSS* Kwiatkowski, Phillips, Schmidt, and Shin, *RW* random walk

$^{*}p < 0.10$

$^{**}p < 0.05$

$^{***}p < 0.01$

Table 4 Unit root tests: Canada

Test	Null hypothesis			CA_t	$Brent_t$	$REER_t$	$POdiff_t$	$RSRV_t$	Imp_t	ΔCA_t	$\Delta Brent_t$	$\Delta REER_t$	$\Delta POdiff_t$	$\Delta RSRV_t$	ΔImp_t
ADF	Null hypothesis: unit root	RW without a drift	*Z*(*t*)	−0.9758	−0.5182	−0.4144	−0.5733	2.7542	−1.1263	***−7.8703******	***−6.4392******	***−6.4368******	–	***−8.8481******	***−6.8324******
		RW with a drift	*Z*(*t*)	−2.1189	−2.0539	−1.1030	***−5.9019******	−0.1307	***−2.7222****	***−7.9053******	***−6.3757******	***−6.3896******	–	***−9.8360******	***−6.7950******
		RW with an unrestricted constant, time trend in regression	*Z*(*t*)	−2.3222	−2.0611	−2.1495	***−5.8506******	−2.6028	−2.5980	***−7.9100******	***−6.3757******	***−6.4128******	–	***−9.8327******	***−6.7685******
GLS	Null hypothesis: unit root	Test statistic		−2.1974	−1.8899	−1.6630	***−5.8926******	−2.0025	−2.2650	***−8.0220******	***−6.4160******	***−6.0950******	–	***−9.8800******	***−6.7651******
		Minimum SIC		0	0	0	0	0	0	***0***	***0***	***0***	–	***0***	***0***
PP	Null hypothesis: unit root	RW with a constant without a time trend	*Z*(*t*)	−1.9687	−2.2450	−1.1031	***−5.9506******	0.0142	−2.5855	***−8.6432******	***−6.2730******	***−6.4031******	–	***−9.6341******	***−7.3409******
		RW with an unrestricted constant, time trend in regression	*Z*(*t*)	−2.1710	−2.1994	−2.2508	***−5.8972******	−2.5505	−2.4330	***−11.6640******	***−6.2755******	***−6.4208******	–	***−9.6385******	***−8.6899******
KPSS	Null hypothesis: level stationary	With a constant	LM-statistic	***0.5937******	***0.1816******	***0.5797******	***0.0689******	0.8716	***0.2488******	***0.2374******	***0.1327******	***0.1628******	–	***0.1625******	***0.2241******
	Null hypothesis: trend stationary	With a constant and a linear trend	LM-statistic	0.2183	***0.1743******	***0.1933******	***0.0631******	***0.1452******	***0.1878******	***0.2085******	***0.0590******	***0.0509******	–	***0.1145******	***0.1666******

Results are reported for seasonally adjusted variables. The Brent oil price and reserves are in logs. The time sample is 2005Q1 to 2019Q1. Values in bold italics indicate stationary variables. *ADF* augmented Dickey–Fuller, *GLS* generalized least squares, *PP* Phillips–Perron, *KPSS* Kwiatkowski, Phillips, Schmidt, and Shin, *RW* random walk

$^{*}p < 0.10$

$^{**}p < 0.05$

$^{***}p < 0.01$

Table 5 TAR results: Saudi Arabia

	Model 1	Model 2	Model 3	Model 4	Model 5
Variable	Dependent variable: change in NFA to GDP ratio (1980–2017)	Dependent variable: current account to GDP ratio (1980–2018)	Dependent variable: budget balance to GDP ratio (1980–2018)	Dependent variable: budget balance to GDP ratio (1980–2018)	Dependent variable: change in NFA to GDP ratio (1990–2017)
Oil-price threshold	*Brent <15.0*	*Brent <29.3*	*Brent <18.1*	*Brent <24.7*	*Brent <38.2*
Change in NFA to GDP ratio (−1)	0.9657(***4.7151******)				
Log of Brent	1.0615(***2.5418*****)	7.7230(***2.6362*****)			
REER	−0.0004(−0.2884)	0.0266(1.2379)	0.1002(***4.5653******)	0.21(***5.3148***$***$)	−0.0029(***−2.0955***$**$)
Budget balance to GDP ratio		0.7301(***7.6400******)			
Budget balance to GDP ratio (−1)			0.8082(***7.5799******)	0.2899(***2.475***$**$)	
Adjusted savings to GNI ratio					0.00329(***2.604***$**$)
Fateh-Brent oil price differential			−3.4701(***−2.4537*****)		
Military expenditure to GDP ratio				−2.45066(***−2.95***$***$)	
Oil-price threshold	*15.0 ≤ Brent <61.6*		*18.1 ≤ Brent <28.7*		
Change in NFA to GDP ratio (−1)	0.3223(***2.4222*****)				
Log of Brent	0.1015(***3.8346******)				
REER	0.0011(1.5689)		−0.5012(***−4.9789******)		
Budget balance to GDP ratio					

(continued)

Table 5 (continued)

Variable	Model 1 Dependent variable: change in NFA to GDP ratio (1980–2017)	Model 2 Dependent variable: current account to GDP ratio (1980–2018)	Model 3 Dependent variable: budget balance to GDP ratio (1980–2018)	Model 4 Dependent variable: budget balance to GDP ratio (1980–2018)	Model 5 Dependent variable: change in NFA to GDP ratio (1990–2017)
Budget balance to GDP ratio (−1)			0.3575(***3.9277******)		
Adjusted savings to GNI ratio					
Fateh-Brent oil price differential			−1.5557(−1.5210)		
Military expenditure to GDP ratio					
Oil-price threshold		*29.3 ≤ Brent <61.6*	*28.7 ≤ Brent <65.6*	*24.7 ≤ Brent <65.6*	*38.2 ≤ Brent <72.6*
Log of Brent		0.3112(0.1174)			
REER		−0.0952(***−6.3973***)***	−0.0170(−0.5714)	0.07278(1.615)	−0.0567(***−3.5174******)
Budget balance to GDP ratio		0.5200(***6.4366******)			
Budget balance to GDP ratio (−1)			0.6399(***4.7091*****)	0.5967(***5.039******)	
Adjusted savings to GNI ratio					−0.038(***−4.4717******)
Fateh-Brent oil price differential			−3.0377(***−2.1672*****)		
Military expenditure to GDP ratio				−2.45066(***−3.4594******)	
Oil-price threshold	*61.6 ≤ Brent*	*61.6 ≤ Brent*	*65.6 ≤ Brent*	*65.6 ≤ Brent*	*72.6 ≤ Brent*
Change in NFA to GDP ratio (−1)	0.0740(0.4770)				

Log of Brent	0.4570 (***4.1650******)	12.0512 (***2.9802******)			
REER	0.0133 (***2.5188*****)	0.4584 (***1.8102****)	−1.8391 (***−5.1873******)	−1.2287 (***−2.9829***$***$)	−0.0282 (***−4.1653***$***$)
Budget balance to GDP ratio		1.0447 (***7.3065******)			
Budget balance to GDP ratio (−1)			−0.0874 (−0.3947)	−0.1966 (−1.261)	
Adjusted savings to GNI ratio					−0.0151 (***−2.619***$**$)
Fateh-Brent oil price differential			−4.3362 (***−2.5788*****)		
Military expenditure to GDP ratio				−5.646 (***−3.058***$***$)	
Dummy variables	DV15 (***3.1548******)	SB00 (***1.8232****)		DV15 (***2.2479*****)	
	SB86 (***2.0753*****)				
Coefficient covariance matrix	Ordinary: same errors across breaks	Ordinary: allow error distributions to differ across breaks	Ordinary: allow error distributions to differ across breaks	Ordinary: same errors across breaks	Ordinary: same errors across breaks
Threshold significance level	0.01	0.01	0.01	0.1	0.01
Delay parameter	4	4	2	2	5
Autocorrelation: LM test; H_0: no serial autocorrelation					

(continued)

Table 5 (continued)

	Model 1	Model 2	Model 3	Model 4	Model 5
Variable	Dependent variable: change in NFA to GDP ratio (1980–2017)	Dependent variable: current account to GDP ratio (1980–2018)	Dependent variable: budget balance to GDP ratio (1980–2018)	Dependent variable: budget balance to GDP ratio (1980–2018)	Dependent variable: change in NFA to GDP ratio (1990–2017)
1 lag 2 lags	0.59003.1440	0.09921.0794	0.37511.0368	0.33670.2898	0.930765.264214
Heteroskedasticity test					
ARCH	$X^2(1)p = 0.7921$	$X^2(1)p = 0.1057$	$X^2(1)p = 0.0321$	$X^2(1)p = 0.6967$	$X^2(1)p = 0.8187$
Breusch–Pagan–Godfrey (H_0: Homoskedasticity)	$X^2(13)p = 0.1362$	$X^2(12)p = 0.5411$	$X^2\ (15)p = 0.3865$	$X^2(12)p = 0.095$	$X^2(5)p = 0.761$
Ramsey test (t-statistic)	0.0371	1.1228	1.2262	1.368327	0.351549
Normality test (Jarque Bera)	0.6405	1.3684	0.6580	0.509694	5.224534
Wald test Restrictive model, 0 breaks	$X^2(6)p = \boldsymbol{0.000}^{***}$	$X^2(6)p = \boldsymbol{0.000}^{***}$	$X^2(9)p = \boldsymbol{0.000}^{***}$	$X^2(6)p = \boldsymbol{0.000}^{***}$	$X^2(4)p = \boldsymbol{0.000}^{***}$
Restrictive model, 2 lower threshold regimes merged into 1 regime	$X^2(3)p = \boldsymbol{0.000}^{***}$	$X^2(3)p = \boldsymbol{0.000}^{***}$		$X^2(3)p = \boldsymbol{0.0007}^{***}$	$X^2(2)p = \boldsymbol{0.000}^{***}$
Restrictive model, 3 lower threshold regimes merged into 1 regime			$X^2(6)p = \boldsymbol{0.000}^{***}$		
SSR	0.0315	180.3101	274.3248	305.3585	0.02285
AIC	−3.5218	5.1243	5.7576	5.7469	−3.63028
BIC	−2.9185	5.6903	6.4613	6.3246	−3.20207
HQIC	−3.3072	5.3239	6.0032	5.9463	−3.499

Values in bold italics indicate significance of the variable and rejection of the null hypothesis

$^{*}p < 0.10$

$^{**}p < 0.05$

$^{***}p < 0.01$

Model 1 has the smallest values for SSR and information criteria (i.e., AIC, BIC, and HQIC), followed by Models 2 and 3.[19]

Models 1–3 show that we can account for the impact of the oil price differential variable on the current account to GDP ratio (and the change in NFA to GDP ratio) indirectly through its impact on the government budget to GDP ratio. A USD 61.60/barrel oil-price threshold effect is significant at the 1% significance level in Models 1 and 2, and a USD 65.61/barrel oil-price threshold effect is significant at the 1% significance level in Model 3, suggesting that an oil price of USD 61–65/barrel or below is not good news for Saudi Arabia. Our estimates are within the range of the IMF (FRED n.d.) external breakeven estimates for Saudi Arabia and are between the 2015 oil exporters' composite breakeven price of USD 56/barrel and the Saudi breakeven price of USD 70/barrel estimated by Setser and Frank (2017).[20] Our results explain why, in the summer of 2019, Saudi Arabia was not comfortable with a USD 60/barrel oil price and was willing to cut production to pull oil prices upward (Paraskova, 2019b). The estimated oil-price threshold levels of USD 15–18/barrel and USD 27–29/barrel are consistent, respectively, with the full cycle breakeven costs of production reported by Büyükşahin et al. (2016), and Aramco's reported funds flow from operations equal to USD 26/barrel in 2018 (Blas et al., 2019).

Moreover, the Brent oil price variable is significant and positive across regimes in Models 1 and 2. In Model 2, the budget balance to GDP ratio has a positive and significant impact on the current account to GDP ratio, suggesting that the Ricardian equivalence does not hold and consumption follows disposable income, causing the current account to be responsive to the fiscal policy. In Model 3, the oil price differential variable has a negative and generally significant impact on the budget balance to GDP ratio across regimes. These results confirm the importance of the oil sector for the Kingdom and the negative impact of geopolitics, regardless of whether a low or high oil-price regime is in place.

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[19] Adding the government budget to the GDP variable in Models 1 and 2 yields a singular covariance matrix. The same applies when including the oil price differential variable or lagged values of the explanatory variables already included in the model. Hence, we do not include the budget balance to GDP ratio, oil price differential variables, lagged oil price, or lagged REER in Models 1 and 2. We examine the budget balance variable in Model 3. If we account for the lagged current account to GDP ratio in Model 2, the model suffers from serial autocorrelation. When we apply the White covariance matrix to address this issue, the results are qualitatively the same as in Models 1 and 2, but the SSR and information criteria are relatively larger; thus, we do not report this model. The data for the current account start in 2006Q1 but the data for GDP start in 2008Q1. Quarterly data for the Arab Light oil price, reserves, and current account to GDP ratio begin in 2002Q4, 2001Q1, 2008Q1, respectively, which restricts the sample size. Results for 2008Q1 to 2019Q1 are qualitatively the same as the annual data model; however, the quarterly data model does not pass all diagnostic tests, so we do not report those results.

[20] Setser and Frank (2017) argue that the Saudi breakeven was USD 50–56 between 2008 and 2012 before rising to USD 70–75 between 2013 and 2015, and decreasing again to USD 50 in 2016; moreover, given Saudi imports and capital outflows in 2016, the breakeven would have been USD 70 on average if the Kingdom had not drawn on reserves.

Razek and McQuinn's (2020) results showed a link between Saudi Arabia's government expenditure and military expenditure. They explained that military expenditure, in other words funds directed to the Ministry of Defense, can be reallocated to the Minister of Interior if internal threats become a priority. Hence, for further robustness, in Model 4, we repeat Model 3 replacing the oil price differential variable with the Saudi military expenditure to GDP ratio to capture geopolitical effects. The results in Model 4 are robust to this variation of the model.

4.2 Russia

As shown in Table 6, we examine the ratio of the current account to GDP (dependent variable), the lagged value of the dependent variable, the primary budget balance to GDP, Brent, official international reserves, REER, and the propensity to spend oil revenues on imports. To capture the impacts of sanctions and pipeline politics, we use the Ural-Brent oil price differential and refinery margin, thereby ensuring robustness. The Brent oil price, oil price differential, and refinery margin are depicted in Fig. 5.[21]

In Table 6, Models 1 and 2 yield the same qualitative results; however, Model 1 has relatively smaller values for the SSR and information criteria than Model 2, confirming the appropriateness of allowing residuals to differ across regimes. Results are robust when replacing the Ural-Brent oil price differential in Model 1 with Urals Hydroskimming Mediterranean Refinery Margin (USD/barrel)[22] in Model 3.

The results show two oil-price thresholds: one at approximately USD 57.7–58.5/barrel and another at approximately USD 46.8/barrel. The propensity to spend oil revenues is significant and negative across all models when the oil price exceeds the USD 46.8/barrel threshold; however, it is insignificant under the low oil-price regime. This could be linked to the import substitution policy promoted by the government to deal with sanctions and adverse economic conditions. The primary budget balance variable has a positive and significant impact under the low oil-price regime (<USD 46.80/barrel) and an insignificant impact under the high oil-price regime (>USD 57–58/barrel). A justification is that under the low oil-price regime,

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[21] Graphical analysis and correlation values show that using the Brent oil price and the oil price differential (correlation: 0.1667) or the oil price and the refinery margin (correlation: −0.14) does not result in multicollinearity.

[22] Refinery margin is an indicator of economic performance. Typically, it is the difference between the value of final refined products and the cost of feedstock (e.g., crude oil) and reflects the impact of market conditions on refinery profitability (McKinsey, n.d.; EIA, 2011). When repeating Model 3 in Table 6, replacing the Urals Hydroskimming Mediterranean Refinery Margin with Urals Cracking Mediterranean Refinery Margin yields, results are qualitatively the same (available upon request). For details on the difference between Hydroskimming and Cracking, refer to Kaiser (2017).

Table 6 TAR results: Russia, 2002Q1 to 2019Q1 (dependent variable: current account to GDP)

Variable	Model 1	Model 2	Model 3	Model 4
Oil-price threshold	*Brent <46.8*	*Brent <50.1*	*Brent <46.8*	*Brent <50.1*
Current account to GDP ratio (−1)	0.2833 (**_2.0224_****)	−0.0233 (−0.2410)	0.3067 (**_1.9501_***)	0.0035 (0.03507)
Primary budget balance to GDP ratio	0.2844 (**_3.4307_*****)	0.1378 (**_2.1698_****)	0.2064 (**_2.4301_****)	
Adjusted savings to GNI ratio				0.0147 (0.10009)
Log of Brent	13.2045 (**_4.3128_*****)	6.7424 (**_3.9080_*****)	9.4269 (**_3.4387_*****)	5.2945 (**_2.9246_**$***$)
Log of reserves	−4.4800 (**_−4.9234_*****)	−3.2458 (**_−4.4991_*****)	−4.1339 (**_−3.9076_*****)	−2.972 (**_−3.8936_**$***$)
REER	0.0118 (0.2218)	−0.0352 (−1.1935)	0.0444 (0.7264)	−0.0367 (−1.2364)
Marginal propensity to import	1.1520 (1.0654)	−0.7142 (−0.8537)	0.6312 (0.5337)	−0.79163 (−0.85587)
Ural-Brent differential	0.5137 (1.550)	−0.1332 (−0.7221)		−0.38339 (−1.474)
Urals Hydroskimming Mediterranean refining margin (USD/barrel)			0.0242 (0.1813)	
Oil-price threshold	*46.8 ≤ Brent <57.7*	*50.1 ≤ Brent <61.4*	*46.8 ≤ Brent <58.5*	*49.5 ≤ Brent <67.4*
Current account to GDP ratio (−1)	−0.0047 (−0.0583)	0.7125 (**_2.9025_*****)	0.0115 (0.1416)	−0.45695 (**_−2.766_**$***$)
Primary budget balance to GDP ratio	−0.1470 (**_−2.5632_****)	0.3915 (**_3.0543_*****)	−0.1319 (−1.1988)	
Adjusted savings to GNI ratio				−0.7596 (**_−5.6306_**$***$)
Log of Brent	1.771 (0.9194)	−1.0784 (−0.2927)	1.2932 (0.6084)	4.746 (**_1.9339_**$*$)
Log of reserves	−3.2463 (**_−4.0409_*****)	−1.2876 (−0.9531)	−3.0435 (**_−2.2501_****)	−2.7627 (**_−3.3326_**$***$)
REER	−0.0687 (**_−2.6017_****)	−0.2676 (**_−3.2096_*****)	−0.0753 (**_−2.7911_*****)	−0.1769 (**_−2.4214_**$**$)

(continued)

Table 6 (continued)

Variable	Model 1	Model 2	Model 3	Model 4
Marginal propensity to import	−2.3076 (***−2.9425******)	−2.9735 (***−2.0322*****)	−2.5843 (***−3.1033******)	−3.2838 (***−2.9817***$***$)
Ural-Brent differential	−0.1384 (−0.7627)	2.4089 (***2.9448******)		−0.70113 (***−1.7289***$*$)
Urals Hydroskimming Mediterranean refining margin (USD/barrel)			0.0204 (0.1318)	
Oil-price threshold	*57.7 ≤ Brent*	*61.4 ≤ Brent*	*58.5 ≤ Brent*	*67.4 ≤ Brent*
Current account to GDP ratio (−1)	0.1532 (***1.8361****)	0.1010 (1.2509)	0.1130 (1.2632)	0.101335 (1.405)
Primary budget balance to GDP	0.0442 (1.234)	−0.0049 (−0.1282)	0.0236 (0.6656)	
Adjusted savings to GNI ratio				−0.0243 (−0.4204)
Log of Brent	0.4286 (0.3172)	0.6035 (0.4712)	0.2645 (0.1837)	1.5312 (1.4047)
Log of reserves	−0.7375 (−1.1391)	0.3825 (0.5263)	−0.4746 (−0.8113)	0.454 (0.5907)
REER	−0.1289 (***−4.6793******)	−0.1518 (***−5.3798******)	−0.0968 (***−3.2842******)	−0.177 (***−7.1408***$***$)
Marginal propensity to import	−5.1588 (***−7.1743******)	−5.0113 (***−7.2865******)	−4.9296 (***−6.6511******)	−4.6526 (***−7.4648***$***$)
Ural-Brent differential	0.3930 (***2.2402*****)	0.1189 (0.7796)		0.3081 (***1.76428***$*$)
Urals Hydroskimming Mediterranean refining margin (USD/barrel)			0.1733 (***2.1022*****)	
Dummy variables	BLP08Q49Q1 (***3.6283******) SB14Q1 (***2.8617******)	BLP08Q49Q1 (***3.4809******) SB14Q1 (1.6011)	BLP08Q49Q1 (***2.8939******) SB14Q1 (***2.8939******)	BLP08Q49Q1 (***4.48435*****)
Coefficient covariance matrix	Ordinary: allow error distributions to differ across breaks	Ordinary: same errors across breaks	Ordinary: allow error distributions to differ across breaks	Ordinary: same errors across breaks

(continued)

Table 6 (continued)

Variable	Model 1	Model 2	Model 3	Model 4
Threshold significance level	0.01	0.05	0.01	0.01
Delay parameter	1	2	1	2
Autocorrelation: LM test (H_0: no serial autocorrelation)	$X^2(4)$ $p = 0.9502$	$X^2(4)$ $p = 0.498$	$X^2(4)$ $p = 0.9842$	$X^2(4)$ $p = 0.0256$
Heteroskedasticity test				
ARCH	$X^2(1)$ $p = 0.6375$	$X^2(1)$ $p = 0.62945$	$X^2(1)$ $p = 0.6718$	$X^2(1)$ $p = 0.8936$
Breusch-pagan-Godfrey; H_0: Homoskedasticity	$X^2(28)$ $p = 0.7835$	$X^2(28)$ $p = 0.6448$	$X^2(28)$ $p = 0.3078$	$X^2(27)$ $p = 0.7561$
Ramsey test (t-statistic)	1.5591	0.3283	1.8247	1.7349
Normality test (Jarque Bera)	2.8151	1.2000	3.9884	0.675643
Wald test				
Restrictive model, 0 breaks	$X^2(14)$ $p =$ ***0.000****	$X^2(14)$ $p =$ ***0.000****	$X^2(14)$ $p =$ ***0.000****	$X^2(14)$ $p =$ ***0.000****
Restrictive model, 2 lower threshold regimes merged into 1 regime	$X^2(7)$ $p =$ ***0.000****	$X^2(7)$ $p =$ ***0.000****	$X^2(7)$ $p =$ ***0.000****	$X^2(8)$ $p =$ ***0.000****
SSR	21.2828	22.8426	23.4527	22.73441
AIC	2.5022	2.5730	2.5993	2.539244
BIC	3.4412	3.5119	3.5383	3.445838
HQIC	2.8748	2.9455	2.9719	2.898921

Values in bold italics indicate significance of the variable and rejection of the null hypothesis

$^{*}p < 0.10$

$^{**}p < 0.05$

$^{***}p < 0.01$

consumption follows disposable income and the Ricardian equivalence does not hold; hence, the current account is more likely to be responsive to the fiscal policy.

When the oil price is below USD 46.80/barrel, the Brent oil price has a significant positive impact, whereas the oil price differential and refinery margin are insignificant. The opposite is true when the oil price exceeds USD 46.80/barrel. Note that we use the refinery margin variable in place of the oil price differential to ensure the absence of multicollinearity. These results confirm the importance of the oil sector to the Russian economy and suggest that Russia has managed to offset the effects of sanctions. Under the low oil-price regime, the effect of reserves is significant and negative, whereas the effect of REER is insignificant. The opposite is true under the high oil-price regime, and they are both significant when the oil price is between the two regimes.

Our estimate for Russia is consistent with Renaissance Capital's estimated breakeven of USD 56/barrel for the overall fiscal balance (rather than USD 40/barrel for the primary balance), as reported by Aris (2018). Our estimated USD 57–58/barrel threshold is also close to the 2015 oil exporters' composite breakeven price of USD 56/barrel estimated by Setser and Frank (2017). This result also explains why the Russian government recently claimed that an average oil price of USD 60–65/barrel is reasonable (Khrennikova & Tannas, 2019).

The estimated USD 46.80/barrel oil-price threshold also aligns with Aris's (2018) statement that Russia begins making a profit on oil exports at USD 45/barrel. Moreover, Henderson (2015) found that under the new tax regime implemented in January 2015, post-tax cashflow would increase by approximately USD 1/barrel at an oil price of USD 50/barrel; moreover, considering the 50% mineral extraction tax (MET) discount, a company can generate a similar amount of post-tax cashflow at an oil price of USD 50/barrel as it had at USD 100/barrel without discounts. This tax policy has motivated companies to not only work on the recovery of oil at existing brownfield sites but also develop new fields (Henderson & Grushevenko, 2019).[23]

As for the impact of the REER, Kleinberg et al. (2018) explained that although the US dollar is typically used to express breakeven points and oil prices in international trade contracts, it may be more appropriate to state some breakeven points in national currencies. In Russia, a large, well-developed oilfield prices its services in rubles. When the international oil price decreased, the ruble depreciated against the US dollar; however, because their breakeven points in rubles effectively remained the same, therefore, Russian oil companies were affected less severely by the price drop than Western oil companies. Because the ruble depreciated after the oil price collapse in 2014, the Russian government was able to balance its budget at approximately USD 43/barrel in 2018 and decrease domestic oil production costs (Bradshaw et al., 2019).

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[23] Russia has announced a gradual elimination of the current export tax while simultaneously increasing MET royalties, which will not significantly affect the impacts of oil price movements on corporate cashflows, because these changes effectively offset each other (Henderson & Grushevenko, 2019).

Russia's preferential tax system and weak exchange rate are likely to incentivize investment in new production projects (Henderson & Grushevenko, 2019). Russia has made consistent upstream investments during the recent downturn, with the short-term goal of improving resource recovery at large existing brownfield sites in western Siberia and the Volga-Urals basin, and the longer term goal of harnessing new technologies to identify and develop new greenfield sites in eastern Siberia, the Arctic, and the Caspian Sea, and perhaps even tight oil reserves. According to Henderson and Grushevenko (2017), domestic and foreign companies are exploring approaches to extract tight oil without violating sanctions,[24] which suggests a stronger future stance for Russia's oil production than previously predicted, assuming additional sanctions are not imposed and the oil price does not collapse.

Furthermore, the Reserve Fund and National Welfare Fund helped Russia overcome the challenges of oil price variabilities and Western sanctions (Popova et al., 2017). Russia also responded to Western sanctions by implementing an "import substitution" policy to promote the development of "strategically important" industrial capabilities beyond oil and gas production (Bradshaw et al., 2019). After 2014, Russia's foreign economic policy focused primarily on increasing hydrocarbon exports and developing new trade and investment channels with non-Western countries (Bradshaw et al., 2019). Russia signed new contracts to build gas pipelines to China (Power of Siberia) in 2014 and Turkey (TurkStream) in 2016 and announced plans to expand the Nord Stream gas pipeline to Germany in 2015 which received final approval in 2017 (Bradshaw et al., 2019). Since the beginning of 2018, crude oil exports shipped via pipeline to China have been increasing, while those shipped by sea to Europe have been decreasing (Paraskova, 2018).

According to Bloomberg, Russia also seems to have come out as a winner in the wake of recent U.S. sanctions against Venezuela and Iran, as Russian exports of heavy crude have increased to meet global demand formerly met by these two countries (Slav, 2019). In addition, in December 2018, OPEC members agreed to cut heavy crude production, increasing pressure on supply. Although Urals typically trades at a discount to Brent, Urals has narrowed this gap since the US re-imposed sanctions against Iran in 2018 and have even sold at a premium, particularly in key Iranian markets such as the Mediterranean. In 2019, Urals has been priced higher than WTI and less than Brent (although at times higher than Brent).

In summary, our results align with other findings in the literature, emphasizing the importance of the oil sector for the Russian economy and highlighting Russia's ability to weaken the impacts of Western sanctions by strategically developing capacities in industries beyond oil and gas, implementing a preferential tax system, imposing an import substitution policy, developing a foreign economic policy that directs trade and investment away from the West, and using currency depreciation

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[24] Sanctions include restricted access of state-owned enterprises in the energy, defense, and banking sectors to Western financial markets and services; and an embargo prohibiting exports of equipment and technologies used in oil production and exploration, and prohibiting exports of military and dual-use goods to Russia (Christie, 2015).

and the Reserve Fund and National Welfare Fund to its advantage. Moreover, Russia seems to have benefitted from the decrease in global supply of heavy crude in the wake of US sanctions on Iran and Venezuela.

4.3 Canada

We examine the current account to GDP ratio (dependent variable), the lagged value of the dependent variable, Brent, official international reserves, REER, the propensity to spend oil export revenues on imports, and the WCS-WTI oil price differential (Model 1 in Table 7). For robustness, we use the oil and gas sector's capacity utilization instead of the oil price differential variable[25] and the budget balance to GDP ratio instead of the lagged current account to GDP ratio (Model 2).[26] Models 1 and 2 in Table 7 yield smaller values for the SSR and information criteria, confirming that they are the appropriate models.

The results show two oil-price thresholds: one at approximately USD 47–50/barrel and the other at approximately USD 74–76/barrel. The latter estimate is close to the 2015 composite measure of the high oil-price breakeven of USD 78/barrel estimated by Setser and Frank (2017) and is consistent with Burleton and Abdelrahman's (2018) argument that steady US and global expansion since 2017 has supported Alberta's economic recovery; however, the crucial factor has been the increase in the price of crude oil to USD 65–75/barrel.

The estimated oil-price threshold of USD 47–50/barrel reflects the full cycle breakeven costs of Canadian production reported by Büyükşahin et al. (2016). Millington (2018) estimated the breakeven price required to cover operating costs, capital expenditures, taxes, and royalties and to obtain a return on investment for a typical greenfield project and an expansion project; after accounting for transportation and blending costs, the WTI equivalent breakeven prices are USD 60.17/barrel and USD 51.59/barrel, respectively.[27] Note that under a low oil-price

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[25] Figure 6 shows that when the sector is approaching full production capacity and cannot access international markets, the oil-price differential increases. This is clear in the graph, particularly, for the year 2018.

[26] We cannot develop a model that includes both the oil-price differential variable and the budget balance to GDP ratio because it yields a singular covariance matrix. In addition, although using the ratio of crude and bitumen exports to GDP or the oil and gas sector's profit margin instead of the oil price differential yields qualitatively the same results, the resulting models do not pass all diagnostic tests. When removing the oil price differential variable and using a longer time sample (the WCS data begin in 2005), the estimated oil-price threshold is around USD 85/barrel. However, this model does not pass all diagnostic tests and yields relatively larger SSR and information criteria values. Hence, these models are not reported.

[27] Market access, exchange rate, uncertain future oil prices, and capital and operating costs are among the risk factors to a project. Sensitivity analyses show that those estimates may increase or decrease due to changes in operating and capital costs, steam to oil ratio, and discount rate (Millington, 2018).

Table 7 TAR results: Canada, 2005Q1 to 2019Q1 (dependent variable: current account to GDP)

Variable	Model 1	Model 2	Model 3
Oil-price threshold	Brent <47.15	Brent <50.15	Brent <63.76
Current account to GDP ratio (−1)	−0.2343 (***−1.8211****)		
Budget balance to GDP ratio		0.4416 (1.2225)	
Adjusted savings to GNI ratio			0.3273 (***2.8404***$***$)
Log of Brent	−11.3970 (***−7.1674******)	−8.2794 (***−10.7883******)	−5.873 (***−5.204***$***$)
Log of reserves	−14.6707 (***−7.6555******)	−11.8665 (***−10.1818******)	−4.665 (***−7.009***$***$)
REER	−0.5019 (***−5.4387******)	−0.2624 (***−6.3890******)	−0.1353 (***−4.2714***$***$)
Marginal propensity to import	−1.3470 (***−12.9788******)	−0.9249 (***−10.8387******)	−0.6945 (***−6.106***$***$)
WCS-Brent differential	−0.0830 (***−3.0620******)		
Capacity utilization		0.0627 (***2.2824*****)	0.00385 (0.08447)
Oil-price threshold	47.15 ≤ Brent <76.07	50.15 ≤ Brent <74.98	63.76 ≤ Brent <85.56
Current account to GDP ratio (−1)	0.0796 (0.5674)		
Budget balance to GDP ratio		0.9453 (***2.1054*****)	
Adjusted savings to GNI ratio			−0.1799 (−1.143)
Log of Brent	0.3960 (0.2553)	0.0570 (0.0610)	3.635 (***4.217***$***$)
Log of reserves	−3.4665 (***−3.0129******)	−5.7400 (***−5.7330******)	−8.5161 (***−6.3013***$***$)
REER	−0.1116 (***−2.9717******)	−0.0887 (***−2.6907*****)	−0.2363 (***−6.6075***$***$)
Marginal propensity to import	−0.0745 (−0.5686)	−0.1133 (−1.5419)	−0.3426 (***−2.727***$**$)
WCS-Brent differential	−0.0169 (−0.7992)		
Capacity utilization		0.0568 (1.5393)	0.4088 (***3.906***$***$)
Oil-price threshold	76.07 ≤ Brent	74.98 ≤ Brent	85.56 ≤ Brent

(continued)

Table 7 (continued)

Variable	Model 1	Model 2	Model 3
Current account to GDP ratio (−1)	0.1890 (1.2427)		
Budget balance to GDP ratio		0.4074 (0.9392)	
Adjusted savings to GNI ratio			−0.1021 (−0.907)
Log of Brent	4.3622 (**_2.3605_****)	1.1889 1.1207	−0.4355 (−0.4218)
Log of reserves	−2.8420 (**_−2.4422_****)	−6.8342 (**_−9.8622_*****)	−3.0738 (**_−4.0458_**$***$)
REER	−0.1705 (**_−4.0043_*****)	−0.1537 (**_−6.1798_*****)	−0.11087 (**_−3.9339_**$***$)
Marginal propensity to import	0.0005 (0.0027)	−0.4748 (**_−3.9531_*****)	−0.3856 (**_−2.7455_**$***$)
WCS-Brent differential	0.0419 (**_1.9088_***)		
Capacity utilization		0.0527 (1.2348)	0.0435 (0.7875)
Dummy variables	SB08Q3 (**_−4.7054_*****)	SB08Q3 (**_−3.2818_*****) DV15Q1 (**_4.2122_*****)	SB08Q3 (**_−4.2776_*****)
Coefficient covariance matrix	Ordinary: Allow error distributions to differ across breaks	Ordinary: Allow error distributions to differ across breaks	Ordinary: Same errors across breaks
Threshold significance level	0.01	0.01	0.01
Delay parameter	3	3	3
Autocorrelation: LM test (H_0: no serial autocorrelation)	$X^2(4)$ $p = 0.0159$	$X^2(4)$ $p = 0.0479$	$X^2(4)$ $p = 0.0152$
Heteroskedasticity test			
ARCH	$X^2(1)$ $p = 0.2350$	$X^2(1)$ $p = 0.1665$	$X^2(1)$ $p = 0.1652$
Breusch–pagan–Godfrey (H_0: Homoskedasticity)	$X^2(24)$ $p = 0.2589$	$X^2(25)$ $p = 0.0778$	$X^2(24)$ $p = 0.9098$
Ramsey test (t-statistic)	0.7533	0.2554	0.496907
Normality test (Jarque Bera)	0.3636	0.4512	1.78516

(continued)

Table 7 (continued)

Variable	Model 1	Model 2	Model 3
Wald test			
Restrictive model, 0 breaks	$X^2(12)$ $p = \boldsymbol{\mathit{0.000***}}$	$X^2(12)$ $p = \boldsymbol{\mathit{0.000***}}$	$X^2(12)$ $p = \boldsymbol{\mathit{0.000***}}$
Restrictive model, 2 lower threshold regimes merged into 1 regime	$X^2(6)$ $p = \boldsymbol{\mathit{0.000***}}$	$X^2(6)$ $p = \boldsymbol{\mathit{0.000}}***$	$X^2(6)$ $p = \boldsymbol{\mathit{0.000}}***$
SSR	7.1267	3.5801	4.116
AIC	1.6359	0.9825	1.0869
BIC	2.5319	1.9144	1.9829
HQIC	1.9841	1.3447	1.435

When removing the DV15Q1 dummy variable, this model does not pass all diagnostic tests, and the residuals are not normally distributed. Values in bold italics indicate significance of the variable and rejection of the null hypothesis

$^{*}p < 0.10$

$^{**}p < 0.05$

$^{***}p < 0.01$

regime (as was the case during 2016 when oil prices were below USD 50/barrel for most of the year), producers are not motivated to invest in new projects (Büyükşahin et al., 2016).

The reserves and REER variables are significant and negative under all three regimes. Under the low price regime (i.e., <USD 47–50/barrel), the reserves coefficient is relatively larger than in other regimes. The impact of the propensity to spend oil revenues on imports is negative and significant under the low oil-price regime and is generally negative and significant under the other two regimes. Moreover, the coefficient in the low oil-price regime is larger than in the other two regimes. This shows that the negative effect of this variable is more pronounced when oil prices are below USD 47–50/barrel. The impact of the oil price is positive and significant under the high oil-price regime (>USD 74–76/barrel), but negative and significant under the low oil-price regime.

Those results are consistent with Carbone and McKenzie's (2016) findings that a negative oil-price shock is bad for Canada, despite the benefits of lower oil prices and currency depreciation to the manufacturing sector; conversely a positive price shock is good for Canada. Although currency depreciation creates benefits for the manufacturing sector in the form of lower energy prices and more international exports, higher prices of imported consumer goods and lower international and domestic demand for manufactured goods (mainly in oil producing economies) outweigh these benefits.

The oil price differential variable has a negative impact when oil prices are below USD 74–76/barrel. This negative effect is significant under the low oil-price regime (<47–50/barrel). The results also show that this variable tends to have a marginally significant ($p < 0.10$) positive impact when oil prices exceed USD 74–76/barrel. The capacity utilization effect is insignificant when oil prices exceed the USD 47–

50 range; once prices exceed supply costs, the sector is more likely to operate at or near full capacity, thereby decreasing the incremental effect. On the other hand, when prices are below USD 47–50/barrel, the sector does not operate at or near full capacity, meaning additional production capacity exists. The positive impact of capacity utilization and the negative impact of the oil price differential variable under the low-price regime shows that the potential increase in oil production has a positive impact on the Canadian current account conditional on the availability of takeaway capacity to ensure that the positive effect of the increase in production is not offset by a decrease in associated price.

4.4 Environmental Sustainability

To assess the role of environmental sustainability, we replace the budget balance to GDP variable with an adjusted net national savings to gross national income (GNI) variable, which is a measure of sustainability derived by the World Bank.[28] The latter is calculated by adding education expenditure to net national savings and subtracting energy, mineral, and forest depletion; and particulate emissions and carbon dioxide damages (where damages are computed as foregone labor income). Annual data for this variable are available starting in 1990. For Saudi Arabia, due to the restrictive sample size, the oil price variable is included as the threshold variable but not as a regressor. For Russia and Canada, to derive a quarterly series, we assumed the value of the variable was approximately the same for each year. The results for Saudi Arabia, Russia, and Canada are represented by Model 5 in Table 5, Model 4 in Table 6, and Model 3 in Table 7, respectively. The external breakeven becomes approximately USD 67/barrel for Russia, USD 72/barrel for Saudi Arabia, and USD 85/barrel for Canada. Although the threshold level for the oil industry remains approximately the same for Russia, it increases for Saudi Arabia to USD 38/barrel and for Canada to USD 63/barrel. Otherwise, the results are robust.

5 Conclusion

The external breakeven is approximately USD 57–58/barrel for Russia, USD 61–65/barrel for Saudi Arabia, and USD 74–76/barrel for Canada. Oil prices below these threshold levels compromise these countries' abilities to finance their external deficits and obligations to the rest of the world.

Our estimate for Russia is consistent with Renaissance Capital's estimated breakeven of USD 56/barrel for the overall fiscal balance, as opposed to the USD 40/barrel for the primary budget balance. These results explain why, in the summer

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[28] The World Bank adjusted net saving variable is retrieved from CEIC.

of 2019, Saudi Arabia was not comfortable with USD 60/barrel oil price and was willing to cut production to drive oil prices upward, whereas Russia viewed an average oil price of USD 60–65 USD/barrel as reasonable (Blas, 2018; Nabiullina, 2018; Paraskova, 2019a). Moreover, during the March 2020 OPEC meeting, despite the Brent oil price initially dropping below USD 60/barrel due to the coronavirus outbreak, Russia resisted the Saudi-led proposition to reduce production (Smith et al., 2020). The results align with Bordoff's (2020) argument that Saudi Arabia needs to keep in mind that Russia's economy is more resilient than the Saudi economy to adverse oil-price shocks. These results hold, when we include in the model the net national savings variable adjusted for expenditure on education and for environmental damage and depletion. In this case, however, Saudi Arabia's external breakeven is USD 72/barrel which is higher than Russia's USD 67/barrel external breakeven. Although Saudi Arabia's threshold for the oil sector is lower than that for Russia, Saudi Arabia has a higher external breakeven than Russia.

We found that geopolitics has detrimental impacts on Saudi Arabia under all oil-price regimes; however, Russia has managed to weather the impacts of sanctions. To overcome the possibility that current sanctions could affect Russia's long-term competitiveness by slowing its foray into new, more complex resource areas such as tight oil, the Arctic, and deep offshore sites, Russia has been seeking alternate (non-Western) sources of funding and equipment, and has implemented an import substitution policy to incentivize domestic firms to invest in local research and development efforts. To diversify the customer base and sources of investment in infrastructure and upstream projects, and to further dilute the potential impact of the US sanctions, cooperation with Asia has become a priority for the Russian government (IEA, 2018).

Saudi Arabia and Russia underestimated the severity of the COVID-19 demand shock in early March 2020. By March 31, WTI and Brent oil prices rapidly dropped to USD 14.85/barrel and 20.51/barrel, respectively; prompting both countries to call for an emergency meeting by early April 2020. This is consistent with our estimated oil-price threshold levels of USD 15–18/barrel and USD 28–29/barrel that reflect Saudi's full cycle breakeven costs of production and Aramco's 2018 reported funds flow from operations; and the estimated USD 46.80/barrel threshold for Russia that aligns with a company ability to generate post-tax cashflow under the new tax system. Note that when we include the adjusted net national savings variable, that estimated threshold becomes approximately USD 50/barrel for Russia and increases to approximately USD 38/barrel for Saudi Arabia. Although it was imminent that both countries will want to reach a deal (as evidenced by the Agreement reached by mid-April to initially cut crude production by 9.7 mb/d in May 2020, followed by subsequent cuts until April 2022 (OPEC, 2020)), the low oil-price regime would prevail as long as the Covid-19 demand shock persists.

For Canada, the estimated USD 74–76/barrel threshold is close to the composite measure of the high oil-price breakeven of USD 78/barrel estimated by Setser and Frank (2017) and is consistent with Burleton and Abdelrahman's (2018) argument that the likely critical factor behind Alberta's economic recovery would be the increase in crude prices to the range of USD 65–75/barrel. However, when we include the net national savings variable adjusted for expenditure on education and for environmental damage and depletion, Canada's external breakeven increases to approximately USD 85/ barrel. Note that although Canada's financial sector is more developed (IMF, n.d.-b) and its economy is more diversified, our results show that that Canada has lower official international reserves, a larger current account deficit, a higher propensity to spend oil exports on imports, and a higher oil-price threshold than Russia and Saudi Arabia.

The estimated oil-price threshold of USD 47–50/barrel for Canada coincides with the breakeven price for an expansion project to obtain a return after accounting for taxes; royalties; and operating, capital, blending, and transportation costs. Canada is negatively impacted by pipeline politics, particularly when the Brent oil price is below USD 47–50/barrel. Under this low oil-price regime, a potential production increase positively impacts Canada's current account conditional on sufficient takeaway capacity to ensure that a price decrease does not offset the positive effects of a production increase. The results also show that an oil price increase has a negative effect on the Canadian current account when oil prices are below USD 47–50/barrel, supporting the "Dutch disease" argument that an oil price increase hurts other Canadian sectors under a low price regime; however, under the high price regime (>USD 74–76/barrel), positive impacts of higher oil prices, including increased resource wealth and consumer purchasing are sufficient to overcome the challenges associated with "Dutch disease." When the adjusted net national savings variable is included in the model, these results are robust but the model suggests a higher threshold of USD 63/barrel.

The high oil-price regime results show that the Canadian economy benefits from a high oil price. The relatively high oil-price threshold suggests strategies are needed to decrease spending on imports and dependence on oil and increase the economy's resilience to market swings to achieve macroeconomic energy security. As a high-cost producer with limited international market access, the low oil-price regime accentuates the loss in dividends and jobs and represents a challenge that is not confined to oil-producing provinces. In the low oil-price regime, there is less global demand for Canadian output and the depreciated Canadian dollar translates into more expensive imports. Despite following a flexible exchange rate regime, low oil price episodes would put a downward pressure on international reserves.

Annex 1: Theoretical Background

To the extent that the ratio of fiscal balance to GDP is a standard determinant of the current account, adjustment patterns of current accounts may be significantly impacted in oil-exporting countries where most governments exclusively control oil export revenues and thus play a larger role than in other countries (Arezki & Hasanov, 2013; Basher & Fachin, 2013). This section provides an overview of the relationship between the external, fiscal, and national balances and their determinants. To ensure consistency among concepts and classifications, we use the terminologies found in the IMF BPM6 manual.

International Investment Position and Balance of Payments

International investment position (IIP) is a stock measure at a specific point in time (e.g., at the end of the year), whereas the balance of payments (BOP) is a measure of flows over a certain period of time (for instance, a year). Measures of stocks and flows are related (Wang, 2005). IIP is a static that measures the value and composition of residents' financial assets that constitute claims on non-residents' assets, and reserve assets; and residents' liabilities owed to non-residents. An economy's net IIP is an economy's external financial assets minus its liabilities (either positive or negative), which reflects the extent to which a country's net worth is attributable to (or derived from) relationships with other countries. The sum of net IIP and the value of nonfinancial assets is a balancing element on the national balance sheet and reflects the net worth of a country's economy. The IIP is becoming an increasingly important factor in the compilation and analysis of international accounts and is recognized as crucial to understanding sustainability and vulnerability (IMF, 2007a, b; Wang, 2005). The terms net IIP and NFA are used interchangeably (Adler & Garcia-Macia, 2018).

Two major account categories—the current account and the capital and financial account—comprise the BOP. The current account includes the trade balance of goods and services plus net income from abroad (the latter being the sum of net primary income, which includes net employee compensation and net investment income; and net secondary income, which includes net private and government transfer payments) (Makin, 2003; Mark, 2001; Schmitt-Grohe et al., 2016; Wang, 2005). The trade balance of the current account includes royalties, which are accounted for in the services balance (Wang, 2005). All transactions involving capital transfers and trade of non-produced, non-financial assets are included in the capital account.[29] All transactions associated with trade of foreign and domestic assets are included in the financial account.[30] Valuation changes that do not involve a change in ownership (e.g., due to a change in market price or the exchange rate) are not included in the capital and financial accounts, but are reflected in the IIP. When an asset changes hands, the difference between the acquisition price and liquidation price is included in the BOP (Wang, 2005). Although the capital and financial account could include reserve assets, reserve assets are quite different from other financial assets. Because they play such an important role in evaluating a country's

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[29] Nonproduced, nonfinancial assets include natural resources; and contracts, leases, and licenses (Wang, 2005).

[30] The financial account encompasses direct and portfolio investment, financial derivatives, and reserves (IMF, 2007b; Wang, 2005).

external position, reserve assets are often analyzed as a separate category. Therefore, BOP can be described as: current account balance + capital and financial account balance (excluding reserves) + official reserve assets = 0. Thus, the current account balance (i.e., net provision of resources to or from the rest of the world) must match changes in net claims on or net liabilities to the rest of the world (Wang, 2005).

Reserve assets include monetary gold, special drawing rights (SDRs), reserve position in the IMF, and foreign exchange assets held by the monetary authority; and are controlled by the monetary authority and used to finance and regulate the extent of payment imbalances through foreign exchange market intervention (IMF, 2007b; Wang, 2005). If the capital account surplus falls short of the amount necessary to finance the current account deficit, the government may use foreign reserves (Afonso & Rault, 2009). Even though sound reserve policies typically increase resilience to shocks, inappropriate economic policy (fiscal, monetary/exchange rate, and financial) can place a country's capability to manage reserves in serious jeopardy. An economy that follows a fixed exchange rate regime uses reserves to combat downward pressure on its currency. Even an economy with flexible exchange rate regime typically utilizes reserves to guard against unpredictable currency depreciation in foreign exchange markets. Reserves can also be used to defend against significant and rapid capital outflows that could cause investors to lose confidence and lead to a currency crisis (Pollard, 2010). As trade and commerce increase, foreign exchange inflows become more volatile; thus, a minimum level of international reserves must be maintained (Nandi, 2014).

The Relationship Between External Balance, Fiscal Balance, and National Accounts

The current account can be described as the change in NFA or as the difference between national savings and investments. The accumulation equation for NFA is used to identify the current account balance at which NFA is stabilized at a given level. The equation, in which NFA is denoted by B_t^*, states that changes in NFA are attributable to either purchases of foreign and domestic assets or associated valuation changes:

$$\mathrm{CA}_t + \mathrm{KG}_t + E_t = B_t^* - B_{t-1}^* = S_t - I_t \tag{6}$$

where CA_t is the current account balance, KG_t represents capital gains due to valuation changes, and E_t includes factors that can cause discrepancy between current account balance and net financial flows, such as capital account transfers, errors and omissions. Assuming $E_t = 0$ (i.e., perfect alignment between the current account and net financial flows) and zero capital gains, Eq. (6) becomes (Lee et al., 2008; Makin, 2003; Mark, 2001; Wang, 2005;):

$$\mathrm{CA}_t = \left(B_t^* - B_{t-1}^*\right) = \left(S_t - I_t\right) \tag{6'}$$

The country's NFA position, B_t^*, equals the sum of public and private assets: $B_t^* = B_t^{*g} + B_t^{*p}$. Domestic savings ($S_t$) and investments ($I_t$) can be unequal if borrowing and lending activities are permitted between domestic and foreign residents. If a country's savings exceed domestic investments by the government and the private sector, the country will have available surplus capital for foreign investment; conversely, if domestic investments exceed savings, extra capital must come from foreign entities. When a country has a current account deficit, residents' net debts to the rest of the world are increasing; to pay the interest on the accumulated debts, domestic consumption must decrease at some point, directing national output toward net exports instead (Makin, 2003; Mark, 2001; Wang, 2005).

The balance between savings (S_t) and investments (I_t) is closely tied to the balance between imports and exports. Total domestic absorption, A_t, is divided between domestic goods (A_t^{d}) and imports (IM_t). Moreover, domestically produced goods are either sold in the domestic market (A_t^{d}) or exported (X_t). Therefore, $Q_t = A_t^{\mathrm{d}} + X_t$. A country's trade balance is the difference between the value of exports and the value of imports: $\mathrm{TB}_t = X_t - \mathrm{IM}_t$. Exports equal total domestic output minus domestic consumption ($X_t = Q_t - A_t^{\mathrm{d}}$); thus, $\mathrm{TB}_t = X_t - \mathrm{IM}_t = Q_t - A_t^{\mathrm{d}} - \mathrm{IM}_t = Q_t - A_t$. In other words, the trade balance equates to GDP minus absorption, and the current account equates to gross national product (GNP) minus absorption (where GNP equals GDP plus net income from abroad and the current account equals the trade balance plus net income from abroad) (Makin, 2003; Mark, 2001; Wang, 2005).

Note that S_t and I_t are national savings and investments by the private and government sectors and can be rewritten as the sum of private and government savings ($S_t = S_t^{\mathrm{g}} + S_t^{\mathrm{p}}$) and private and government investments ($I_t = I_t^{\mathrm{g}} + I_t^{\mathrm{p}}$) (Schmitt-Grohe et al., 2016). Hence:

$$\mathrm{CA}_t = \left(S_t^{\mathrm{P}} - I_t^{\mathrm{P}}\right) + \left(S_t^{\mathrm{g}} - I_t^{\mathrm{g}}\right) \tag{7}$$

$$\mathrm{CA}_t = \left(S_t^{\mathrm{P}} - I_t^{\mathrm{P}}\right) + \left(rB_{t-1}^{*\mathrm{g}} + R_t - G_t - I_t^{\mathrm{g}}\right) \tag{8}$$

$$\mathrm{CA}_t = S_t^{\mathrm{P}} - I_t^{\mathrm{P}} + rB_{t-1}^{*\mathrm{g}} + \text{Primary Government Budget balance} \tag{9}$$

$$\mathrm{CA}_t = S_t^{\mathrm{P}} - I_t^{\mathrm{P}} + \text{Overall Government Budget balance} \tag{10}$$

where R_t is government revenues, G_t is government expenditure, r is the interest rate, and $rB_{t-1}^{*\mathrm{g}}$ is the return received at time t on assets held at time $t-1$. $S_t^{\mathrm{g}} - I_t^{\mathrm{g}}$ is the overall fiscal balance. The overall fiscal deficit has two components: interest income on government asset holdings ($rB_{t-1}^{*\mathrm{g}}$) and the primary fiscal balance, which is the difference between government revenues and expenditures (Akanbi & Sbia, 2018; IMF, n.d.-a.; Makin, 2003; Schmitt-Grohe et al., 2016).

The means of deficit financing must be considered in any evaluation of fiscal policy, because each approach is associated with specific macroeconomic implications. When external financing is used, debt accumulates. This debt needs to be serviced and repaid and hence, exposes the economy to exchange rate and world interest rates movements. External financing could lead to currency appreciation, thereby placing downward pressure on exports and driving imports higher. Thus, externally financed deficits must be evaluated based on the prospects of BOP in the medium term (IMF, n.d.-a).

The Medium-Term Macroeconomic Balance Approach

The medium-term macroeconomic balance approach is based on the BOP relationship (Dvornak et al., 2005) and entails estimating the equilibrium relationship between the current account and its determinants and determining the adjustment required to achieve external balance (Lee et al., 2008). External balance is achieved when the value of the underlying current account equals that of the target capital account. The capital account reflects excess domestic savings relative to investments (Dvornak et al., 2005). Isard and Faruquee (1998) and Kincaid et al. (2001) modeled the target capital account based on factors that influence optimal savings and investment decisions, including the savings ratio (to capture agents' consumption smoothing decisions), demographics (e.g., the dependency ratio), relative fiscal position, and capital needs based on development stage (Dvornak et al., 2005). In light of the relationship between the external balance and national accounts, Lee et al. (2008) explained that in addition to fiscal balance, demographics, and capital needs based on development stage and economic growth, mid-term determinants of the current account also include NFA, oil trade balance and oil prices, and economic and banking crises. It is also a function of the real exchange rate, which affects the trade balance via import and export volumes and prices, and the portion of net foreign investment income denominated in foreign currency, and depends on domestic and foreign income levels and other factors that may influence the current account balance (Dvornak et al., 2005).

A country's investment and saving decisions are likely to change in response to the fiscal deficit. The relationship between the current and fiscal balances are affected by the extent of Ricardian equivalence, debt neutrality, and the extent to which the financial market is developed. A low level of public debt and higher policy credibility are associated with a lower likelihood of saving part of a stimulus to stave off future tax increases (Ilzetzki et al., 2013). When public debt is low, the current generation views a future debt stabilization policy as unlikely and expects future tax liabilities to be low. In this case, aggregate demand and savings would be responsive to fiscal adjustments; on the other hand, when public debt is high, future debt stabilization is more likely. Therefore, the relationship between fiscal and external deficits may be stronger when public debt levels are lower. The current account is not affected by the fiscal policy if consumption depends on lifetime income and non-distortionary taxes (i.e., if Ricardian equivalence holds); however, the current account depends on the budget deficit if consumption follows current disposable income (i.e., if Ricardian equivalence does not hold) (Frenkel & Razin, 1996). In countries with relatively underdeveloped financial markets, economic agents are less likely to distribute income over time; thus, fiscal multipliers tend to be larger (Batini et al., 2014). The relationship between fiscal policy and the current account is stronger when financial systems are more regulated or underdeveloped (Frenkel & Razin, 1996).

Moreover, the relationship is affected by the business cycle, as a budget deficit could be attributable to looser fiscal policy or an economic downturn (IMF, n.d.-a). The impact on the current account also depends on a country's size and trade exposure (Afonso & Rault, 2009). Countries that are small and/or closed to trade tend to have less fiscal stimulus "leakage" abroad. However, countries with large and open economies tend to have more fiscal stimulus leakage, which causes fiscal multipliers to shrink (Vlasov & Deryugina, 2018). Without taxes or other measures to restrain demand in the private sector, increased government spending drives growth in imports relative to exports and deterioration of the current account (IMF, n.d.-a).

A sustainable current account balance is not necessarily a long-term equilibrium, which requires a stable NFA to GDP ratio; instead, it could be a medium-term equilibrium which is expected to adjust because factors which determine the target capital account (including, fiscal policy and exchange rates) vary over time (Dvornak et al., 2005).

Summary

According to the BOP equation, the current account balance must equal the capital and financial account balance plus official reserve asset transactions. In other words, the current account balance must match changes in net claims and liabilities to the rest of the world. If the capital account surplus is insufficient to finance the current account deficit, the government may need to use foreign reserves for important activities such as financing and regulating payment imbalances.

The current account is equivalent to the change in NFA or the difference between national savings and investments. Any evaluation of fiscal policy must consider how deficits are financed. If external financing is used to fund a government's budget, it must be assessed in the context of the prospects for BOP in the medium-term, which requires estimating the equilibrium between the current account and its determinants. When the values of the underlying current account and the target capital account are equal, external balance is achieved. Because the capital account reflects the extent to which domestic savings exceed investments, factors that influence optimal savings and investment decisions—including fiscal position, as well as the state of the economic cycle, oil prices and trade balance, NFA and real exchange rate—are considered when modeling the equilibrium current account.

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