Global Sustainability

cambridge.org/sus

Intelligence Briefing

Cite this article: Fankhauser S, Kotsch R, Srivastav S (2020). The readiness of industry for a transformative recovery from COVID 19. *Global Sustainability* **3**, e37, 1–10. https://doi.org/10.1017/sus.2020.29

Received: 20 September 2020
Accepted: 7 October 2020

Key words:
clean innovation; COVID 19; COVID 19 recovery; net-zero emissions; zero-carbon competitiveness; zero-carbon transition

Author for correspondence:
Sam Fankhauser,
E-mail: s.fankhauser@lse.ac.uk

The readiness of industry for a transformative recovery from COVID 19

Sam Fankhauser[1], Raphaela Kotsch[2] and Sugandha Srivastav[3]

[1]Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London School of Economics, London, UK; [2]Institut für Politikwissenschaft, Universität Zürich, Zürich, Switzerland and [3]Institute of New Economic Thinking at the Oxford Martin School, University of Oxford, Oxford, UK

Non-technical summary

Many countries are committed to emerge from COVID 19 on a more sustainable environmental footing. Here we explore what such a structurally transformative recovery would mean for the manufacturing sector of 14 major economies. We find that all countries have zero-carbon growth opportunities post-COVID and comparative advantages in some sectors, but industrialised countries and the East Asian economies, especially South Korea, appear best positioned, thanks a push in low-carbon innovation that predates the pandemic.

Technical summary

We construct two indicators to assess the readiness of manufacturing in 14 countries to move toward zero-carbon products and processes post-COVID 19. The first indicator is the extent to which country-sectors have already started to convert to zero-carbon products and processes. This is measured by the relative low-carbon innovation in different country sectors (using global patent data). The second indicator is the ability of country-sectors to gain and maintain market share. This is measured by existing comparative advantages, using the Balassa index of revealed comparative advantage. Taken together the two indicators paint an intuitive picture of the strengths, weaknesses, opportunities and threats (SWOT) faced by different sectors, which can guide countries in their recovery strategies.

Social media summary

A zero-carbon recovery from COVID must be led by industry. It requires clean innovation based on comparative advantage.

1. Introduction

Coronavirus disease 2019 (COVID 19) struck at a time when the world economy was starting to move towards cleaner, environmentally more sustainable forms of production. The size of the green economy is now on a par with global oil and gas and growing rapidly (FTSE Russell, 2018). The pandemic also hit at a politically important time for international climate action. The parties to the Paris Agreement were expected to review, and ratchet up, their nationally determined contributions to the agreement in the course of 2020. In anticipation, countries such as France, New Zealand, Sweden and the UK had legislated net zero emissions targets (Eskander et al., 2020). Over 1700 jurisdictions in 30 countries have declared a climate emergency (Climate Emergency Declaration, 2020).

To maintain this momentum, there are now calls for a 'great reset' (Schwab & Malleret, 2020) and to 'build back better' (e.g. Allan et al., 2020; Stern et al., 2020), that is, to make the post-COVID recovery Paris-aligned and environmentally sustainable. Much of the emphasis is on fiscal support packages. By June 2020 over US$11 trillion in fiscal support had been committed to cushion the impact of the pandemic on households and firms (Sovacool et al., 2020).[i] As the policy response moves from preservation to recovery, the argument is that a large part of this Keynesian demand boost could be used to simultaneously advance decarbonisation. Promising 'green fiscal stimulus' measures include energy efficiency upgrades for the housing stock, investment in clean infrastructure and nature-based decarbonisation solutions (Hepburn et al., 2020; IEA, 2020; for a more critical stance see Brahmbhatt, 2014).

In addition to this short-term, cyclical (or Keynesian) dimension, there is an important long-term, structural (or Schumpeterian) aspect to a zero-carbon recovery (Bowen & Fankhauser, 2011). In addition to being *timely* and *targeted* (the hallmarks of a good Keynesian stimulus), the zero-carbon recovery also needs to be *transformational* (Allan et al., 2020). That is, it needs to support the long-term structural changes that deep decarbonisation requires, by promoting clean innovation, re-skilling the work force and creating business confidence in the

Table 1. Country groupings

Country	Impact of COVID 19 (2020 fall in GDP, projected)
Brazil (BRA)	7–9
Mexico (MEX)	8–9
China (CHN)	3–4
India (IND)	4–7
South Korea (KOR)	1–2
Taiwan (TWN)	n/a
Poland (POL)	7–10
Russia (RUS)	8–10
Turkey (TUR)	5–8
France (FRA)	11–14
Germany (DEU)	7–9
Japan (JPN)	6–7
United Kingdom (UK)	11–14
United States (USA)	7–9

Note: The range in projected GDP loss is between a single hit and a double hit scenario.
Source: https://data.oecd.org/gdp/real-gdp-forecast.htm (accessed 30 August 2020).

green economy (Zenghelis, 2014). EBRD (2020) also calls for bailout packages to be conditional on industry adopting decarbonisation targets.

However, the prospect for a zero-carbon recovery from COVID 19 depends on business behaviour as much as it does on government action. The zero-carbon transition will fundamentally change the current patterns of industrial production and comparative advantage (Perez, 2019), posing threats and creating opportunities in equal measure. High-carbon activities will inevitably contract, but for the well-positioned, action on climate change will generate opportunities for growth.

This paper explores to what extent industrial sectors are ready to play their part in a transformative, zero-carbon recovery from COVID 19. We are interested in the green competitive position of different countries and sectors as they emerge from the pandemic. These positions were built over many years, well before COVID 19, but they will now shape its aftermath and can help governments design their recovery packages.

The focus is on manufacturing, which is one of the biggest contributors to the green economy globally (FTSE Russell, 2018). Specifically, we consider the manufacturing section in the ISIC Rev 3.1 industry classification, focusing on the 15 largest sectors by economic output in each country.

The paper uses a methodology developed by Fankhauser et al. (2013). Using current economic output as the starting point, we identify two potential indicators of zero-carbon competitiveness at the sector level: the speed at which sectors may convert to zero-carbon products and processes (measured by low-carbon innovation) and their ability to gain and maintain green market share (measured by existing comparative advantages). The two indicators are more structural than the cyclical response to the pandemic. However, taken together, they paint a picture of the long-term strengths, weaknesses, opportunities and threats of different countries and sectors in a zero-carbon recovery.

In emphasising clean innovation, the analysis focuses on a particular type of economy: those that participate in frontier innovation as a source of their competitiveness. We study 14 countries – nine emerging markets and five industrialised economies – for which this is broadly the case (Table 1). They are among the global engines of technological innovation, and include some of the economically most (France and UK) and least (China and South Korea) affected countries by the pandemic. However, it is worth remembering that for many other countries, technological competitiveness does not derive from frontier innovation, but from their technological capabilities and industrial capacity to adopt new technology (Bell & Albu, 1999; Bell & Pavitt, 1993).

The paper proceeds as follows. Section 2 discusses the competitiveness prospects of a zero-carbon recovery from the point of view of countries. Section 3 provides additional detail from a sector perspective. Section 4 concludes with policy implications. A methodological summary is provided in Appendix A.

2. Zero-carbon prospects at a glance

The creation of a post-COVID zero-carbon economy will affect not just a few specialised sectors but the product mix and production processes of virtually the whole economy (Perez, 2019). Some sectors, such as coal mining or petrol refining, will contract, while others, such as recycling or battery production, may grow. But for most sectors, the zero-carbon economy is about adjusting existing products and production processes. The construction sector will specialise in zero-carbon buildings, the financial sector will provide capital for zero-carbon investment and the automotive sector will produce zero-carbon vehicles.

Our conjecture is that the ability of country-sectors to respond to this challenge depends on two key factors, both build over many years. The first is the aptitude of a country-sector to convert existing products and production processes to zero-carbon alternatives. We measure this aspect through green innovation, or more specifically a green innovation index (GII), which puts zero-carbon innovation (measured through patent counts) in relation to overall innovation (see Appendix A for details).

The second factor is existing comparative advantage. The premise is that comparative advantage evolves slowly, and that sectors with a competitive edge today are more likely (but not certain) to be successful in the future, benefitting from the ability to diversify into related technologies (Hidalgo et al., 2007; Mealy & Teytelboym, 2020). We measure comparative advantage through a Balassa index of revealed comparative advantage (RCA), a common measure of the trade literature (Balassa, 1965).

Plotting the two indicators against each other reveals each country's strengths, weaknesses, opportunities and threats from a zero-carbon recovery. Figure 1 measures on the *y* axis the green innovation performance of different sectors and countries (GII). The *x* axis depicts the RCA of those country-sectors (RCA). For both indicators, a score above 1 signifies performance above the sample average and a score below 1 means performance below the sample average. The size of the bubbles measures a sector's current contribution (green and non-green) to national GDP.

Figure 1 can then be interpreted as follows:

(1) Sectors in the top-right quadrant signify *strengths*: these are areas of current comparative advantage (high score on the *x* axis) and there is substantial low-carbon innovation (high score on the *y* axis), which should ease the conversion to zero-carbon products and processes. The sectors are thus well positioned to remain areas of competitive strength in a zero-carbon recovery.

(2) Sectors in the top-left quadrant signify *opportunities*: these are not currently areas of comparative advantage. However, there is significant low-carbon innovation, which could facilitate the conversion to zero-carbon products and processes. The sectors could therefore become new areas of strength, potentially displacing carbon-intensive incumbents.
(3) Sectors in the bottom-right quadrant signify *threats*: these are areas of current comparative advantage, but there is insufficient low-carbon innovation. The conversion to clean products and processes may stall and market share may be lost during a zero-carbon recovery.
(4) Sectors in the bottom-left quadrant signify *weakness*: these are not areas of current comparative advantage, and there is insufficient low-carbon innovation to build up a new area of comparative advantage.

The power of these charts lies in the overall visual impression they create about different countries' position in the zero-carbon economy. We do not assign importance to specific numbers and deliberately omit sector labels. However, some descriptive statistics are provided in Table 2.

The main industrialised economies appear well prepared for a zero-carbon recovery. Global innovation powerhouses such as Germany, Japan and the United States play a leading role in low-carbon innovation, including in the sectors where they already have a comparative advantage. The picture is more mixed for France and the UK,

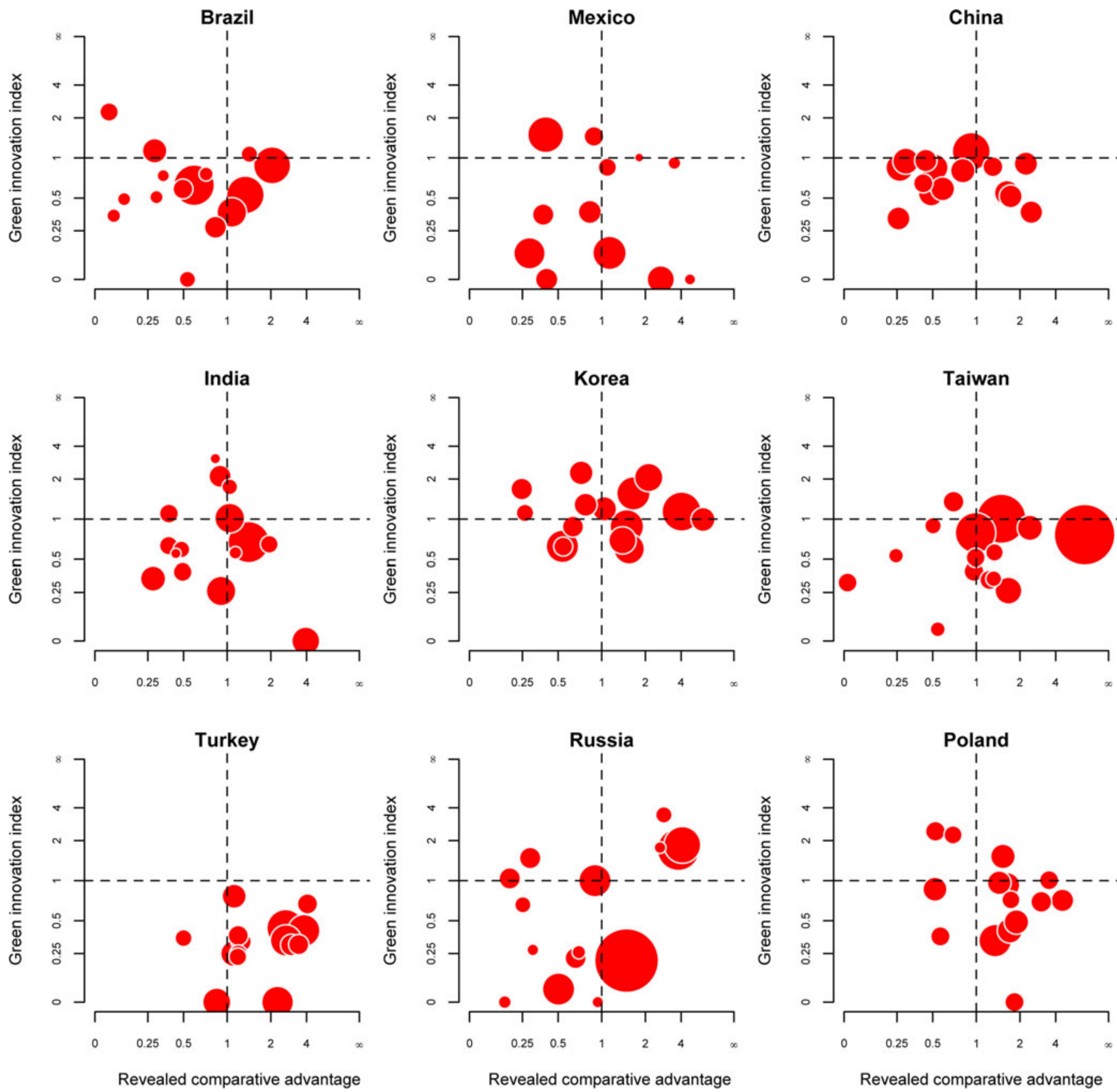

Fig. 1. A low-carbon SWOT: country analysis. *Note:* Each bubble indicates the location of a country-sector on the GII–RCA plane. The size of the bubble indicates the size of the country-sector, using output data from UNIDO. For each country, the analysis considered the 15 largest manufacturing sectors (in terms of output) with at least 20 patents revealed comparative advantage. *Source:* Own calculations.

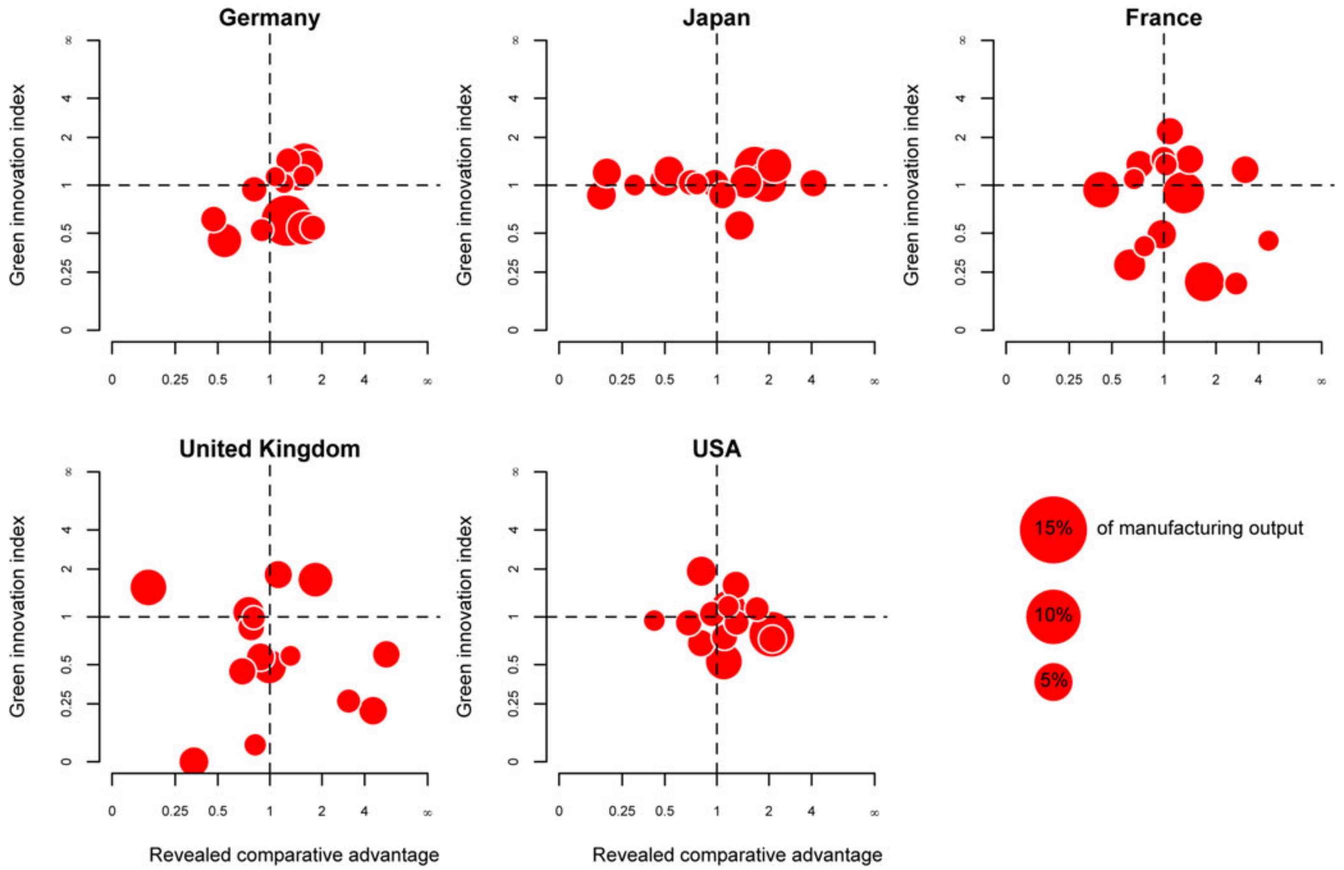

Fig. 1. Continued.

Table 2. Descriptive statistics on green innovation

	Green patents (numbers)	Green patents (share of total) (%)	Range in GII scores (min/max)	Range in RCA scores (min/max)
Brazil	185	5.8	0.00–2.22	0.06–2.03
Mexico	26	4.2	0.00–1.47	0.29–5.01
China	14,330	5.7	0.33–1.11	0.26–2.42
India	314	4.0	0.00–2.98	0.28–3.93
South Korea	41,925	9.8	0.61–2.23	0.25–7.55
Taiwan	6872	4.0	0.05–1.33	0.01–10.06
Poland	274	9.3	0.00–2.37	0.52–4.74
Russia	229	8.7	0.00–3.36	0.15–4.12
Turkey	140	3.7	0.00–0.77	0.50–4.10
France	6638	14.9	0.45–1.42	0.47–1.75
Germany	27,180	11.5	0.19–2.19	0.43–4.93
Japan	134,851	9.7	0.57–1.31	0.15–4.16
UK	2465	9.6	0.00–1.82	0.13–6.64
USA	35,439	11.0	0.53–1.92	0.43–2.09

Source: Own calculations from EPO.

which display more weaknesses and threats than for example the emerging East Asian economies. However, overall it appears that the leading industrialised countries have little to fear from a zero-carbon recovery.

Among emerging markets, the East Asian countries, especially South Korea, appear best placed to prosper in a zero-carbon world. Their levels of low-carbon innovation are close to or above world average, with the majority of innovation scores above 0.8, including in the most important sectors economically. However, certainly in China and Taiwan there are also weaknesses and threats to existing economic positions, for example in the automotive sector in the case of China and metals in the case of Taiwan.

South Korea is an instructive example of how a robust innovation ecosystem and explicit support for low-carbon industries (Jones & Yoo, 2011; Mathews, 2012) can combine to produce a favourable position in the zero-carbon economy. Almost all of South Korea's sectors are located in the top two quadrants of Figure 2. In 2009, South Korea became one of the first countries in the world to release a national law on low-carbon green growth, which explicitly promotes eco-friendly engines of growth. Our analysis suggests that this strategy of developmental environmentalism (Kim & Thurbon, 2015) is bearing fruit.

China has pursued a similar strategy with the same success in its five-year plans. Starting with the 12th Five-Year Plan (2011–15) China has put forward support for strategic green industries (Green & Stern, 2017; Stern, 2011). The 12th Five-Year Plan puts in place a host of preferential policies, such as tax exemptions and reductions, special financing arrangements and favourable loan terms for clean energy and energy efficiency projects. The 13th Five-Year Plan (2016–20) has continued the momentum for green growth by setting targets for increasing the efficiency of industries, using more renewable energy and developing green infrastructure.

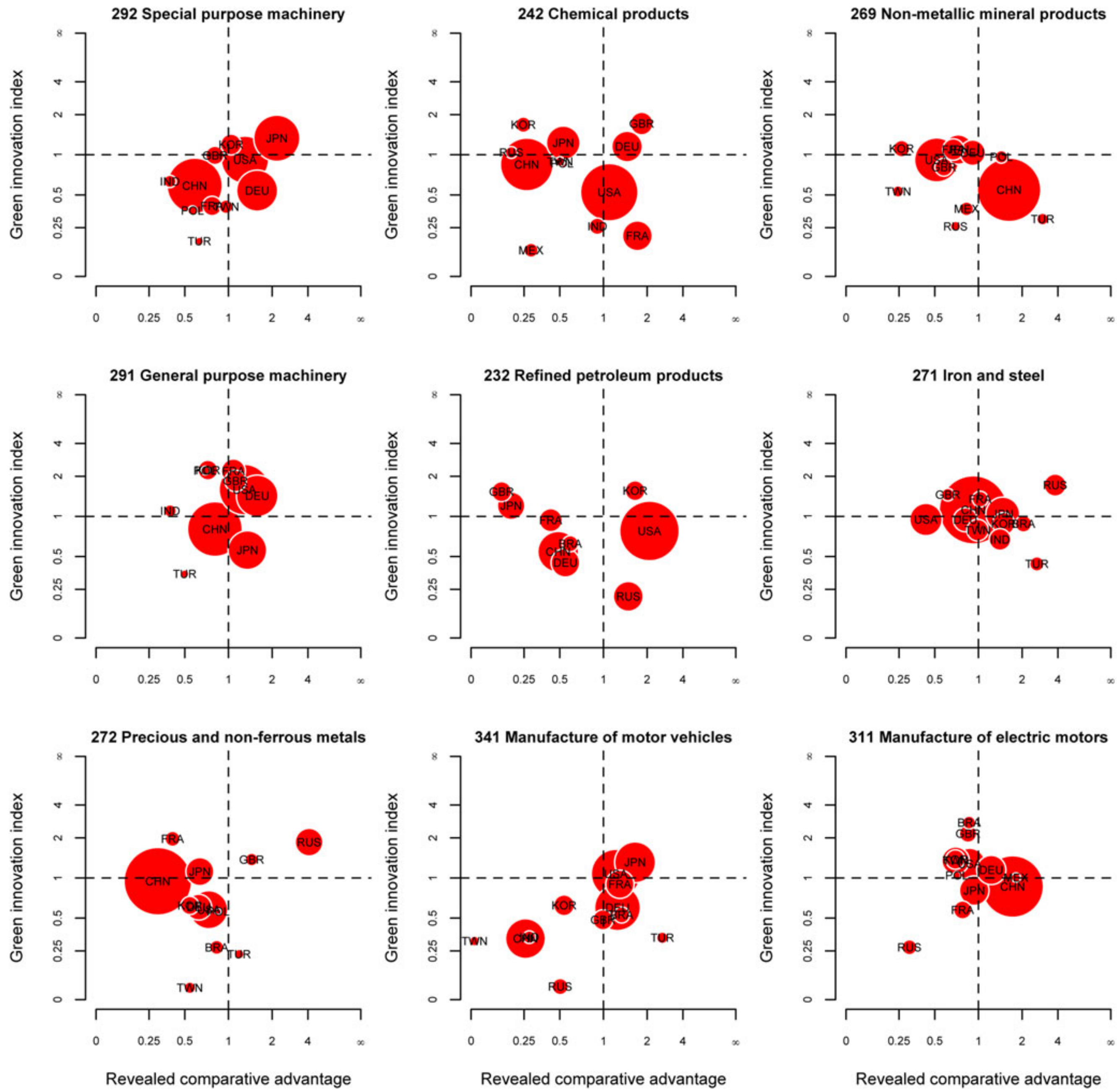

Fig. 2. A low-carbon SWOT: sector analysis. *Note*: See Figure 1 for further explanation. *Source:* Own calculations.

In Emerging Europe, Latin America and South Asia the picture is less favourable. Patent counts are noticeably lower (Table 2) and green patenting is scarce, as reflected in the large concentration of sectors at the bottom of the chart. The zero-carbon outlook is particularly precarious for Turkey, where clean innovation is some distance from the world average in all sectors. Russia is a mixed bag. It has a cluster of sectors that specialise in low-carbon innovation and which also have an entrenched comparative advantage (e.g. metals). However, it also has important sectors, such as refined petroleum products, which underperform on clean innovation.

Low-carbon innovation in these countries is often aimed at reducing materials cost and increasing energy efficiency. For example, Brazil, India, Russia and Turkey have all seen green innovation in iron and steel, a sector in which costs (and emissions) can be dramatically reduced through resource efficiency measures such as the re-use of slag (a by-product of steelmaking) and by switching to electric arc furnaces which re-use scrap steel.

Mexico's case is interesting because it highlights the differences between green growth policies, which are aimed at supporting low-carbon business, and climate change policies, which aim to reduce emissions. Mexico is considered a progressive country on climate change, with a thoughtful legislative framework (Averchenkova & Guzman Luna, 2018). However, in the absence of complementary industrial and innovation policies (OECD, 2008), this has not so far resulted in a favourable competitive position in the zero-carbon economy.

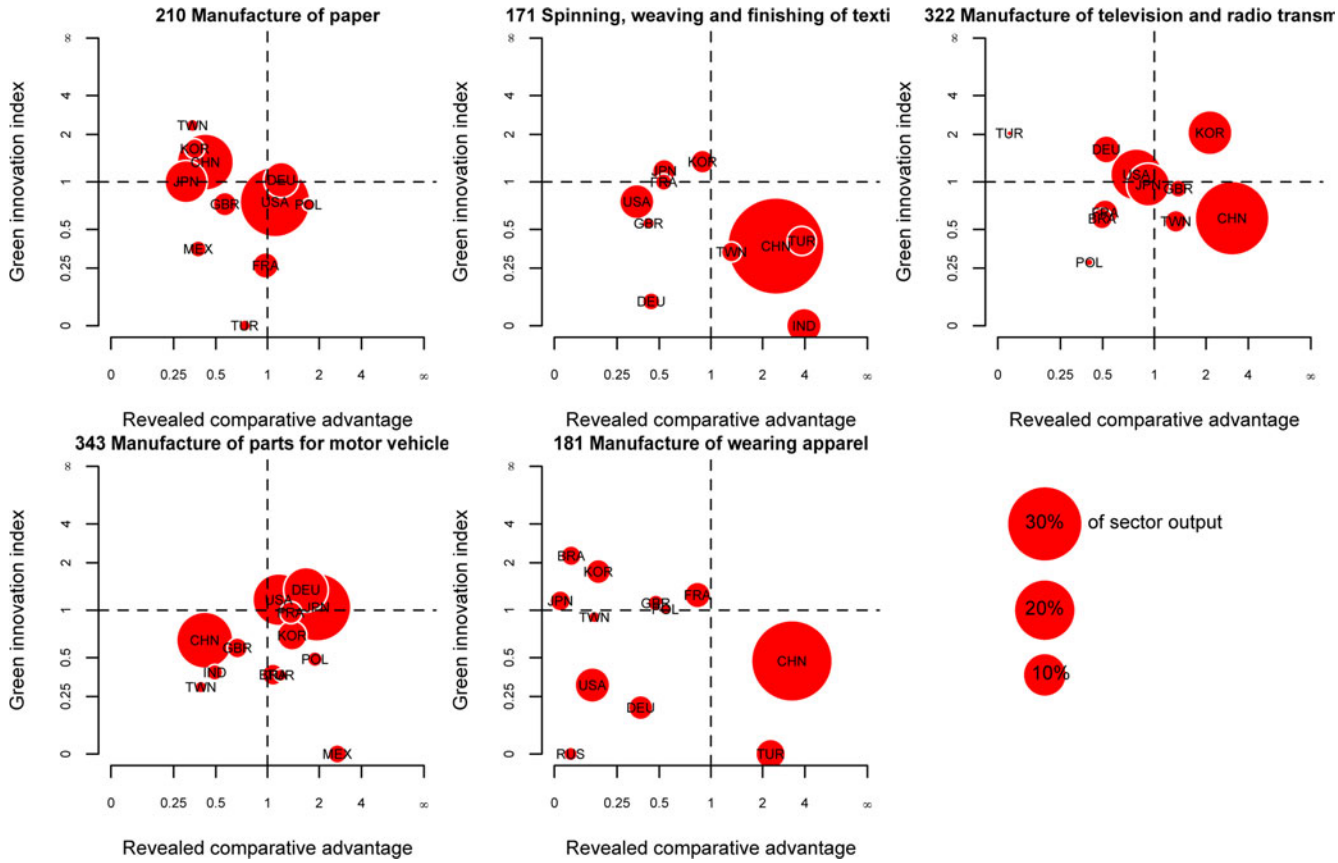

Fig. 2. Continued.

3. Some sector specifics

The previous section offered a deliberately broad, visual impression of industrial competitiveness under a zero-carbon recovery. We now complement this picture with some sector details. We look at 14 sectors that are of strategic importance to the zero-carbon transition.

Figure 2 shows equivalent strengths, weaknesses, opportunities and threats (SWOT) charts to Figure 1, but this time from a sector perspective. That is, each chart plots the location of different countries on the GII–RCA plane in a particular sector. The charts allow us to speculate how disruptive a zero-carbon recovery might be. In some sectors, the move to net zero emissions could dramatically change the competitive landscape. In other sectors, the prevailing order may continue.

We gauge the likelihood of disruption by looking at the correlation between GII and RCA scores. A zero-carbon recovery is more likely to lead to disruption in sectors where that correlation is negative, that is, where countries are clustered in the top-left and bottom-right quadrants of Figure 2. In these sectors, there is a high prevalence of countries that either face threats to their current position (low GII, high RCA) or have new economic opportunities (high GII, low RCA). In such a setup, incumbent operators could lose market share to zero-carbon newcomers.

Conversely, a zero-carbon recovery is less likely to be disruptive in sectors where the correlation between GII and RCA is positive. In these sectors, countries are clustered in the bottom-left and top-right quadrants of Figure 2. Existing market structures are more likely to prevail because incumbent countries have considerable strengths (top-right quadrant) and they face few apparent challenges from weak newcomers (bottom-left quadrant).

3.1. Potential for disruption

Table 3 displays the correlation coefficients (Pearson's *R*) for the 14 sectors we consider. In six of them the GII–RCA correlation is negative, suggesting threats to incumbents and opportunities for newcomers.

The clothing industry is an instructive example (ISIC codes 171 and 181). Green innovation in these sectors relates mostly to more energy-efficient production methods rather than more salient or radical low-carbon innovation. Turkey seems to do little to convert its production processes to energy-efficient and low-carbon alternatives and could lose market share to newcomers such as South Korea. China, which commands a sizeable proportion of the global textiles market, also appears at risk. However, the country has an entrenched comparative advantage, with extremely competitive labour costs. As such, any takeovers in this sector may be slow, if they happen at all, even though low-carbon innovation is not driven by the current market leaders.

In the chemical sector, industrialised countries such as UK and Germany have both a current comparative advantage and green innovation specialisation. As such they are likely to maintain their competitive position. However, elsewhere there could be disruption. France and to a lesser extent the United States risk losing market share to low-carbon newcomers such as South Korea, Japan and China, which are innovating in low-carbon chemical processes. If these countries can leverage their patents

Table 3. Likelihood of disruptive change in sector competitiveness

Disruption in competitiveness	Sector	ISIC Rev3	Correlation coefficient
Likely	Spinning, weaving and finishing of textiles	171	−0.386
	Non-metallic mineral products	269	−0.363
	Paper	210	−0.350
	Wearing apparel	181	−0.314
	Iron and steel	271	−0.030
	Chemical products	242	−0.002
Less likely	Parts for motor vehicles	343	0.043
	Electric motors	311	0.048
	Refined petroleum products	232	0.051
	General purpose machinery	291	0.096
	Motor vehicles	341	0.144
	Television and radio transmitters	322	0.309
	Precious and non-ferrous metals	272	0.337
	Special purpose machinery	292	0.642

Source: Own calculations from EPO.

in catalysts, electrolysis and CO_2 absorption methods as part of a zero-carbon recovery, they may be able to expand their market share.

3.2. Strong incumbents

In the eight sectors with a positive GII–RCA correlation market disruption is less likely, although not impossible. In the market for refined petroleum products (ISIC code 232), zero-carbon innovation is creating new final products, such as biofuels, rather than simply triggering process-related improvements. Leaders in biofuels include the United States and South Korea, which enjoy both a comparative advantage and high levels of green innovation, should be able to retain their competitive position.

The United States plays a leading role in the transformation of refined petroleum products, helped by policies which date back to the 1990s. The US government ramped up mandatory quantity targets for biofuels, creating the space for growth and innovation in the sector (although not always to the benefit of the natural environment, Scharlemann and Laurance, 2008). In contrast, Russia could lose market share to low-carbon innovators such as Japan, France and the UK, whose notable innovations include biofuel improvements and carbon capture and storage. Brazil has not been able to turn its experience in sugar cane biofuels into a global competitive edge.

The market structure in the automotive sector (ISIC codes 341 and 343) also appears stable. Countries that have an entrenched comparative advantage in conventional automotives find it easier to diversify into zero-carbon vehicles, leveraging their existing manufacturing capabilities and skills. The development of hybrid and electric vehicles has been led by Japan, the United States, Germany and other European countries that have an entrenched comparative advantage in the auto industry and which could leverage their existing skills base to develop an 'adjacent' green technology (Unsworth et al., 2020). Of course, a stable constellation at the level of countries does not preclude market entry and exit at the level of firms, as we could witnessed for example in the US automotive market.

4. Conclusions

COVID 19 will have a significant impact on climate change policy. The pandemic will shape both the economic context in which climate policy takes place (Helm, 2020; Hepburn et al., 2020), and public attitudes towards these measures (Howarth et al., 2020). Even measured commentators were quick to draw parallels between COVID 19 and climate risks. The International Monetary Fund noted that 'as with pandemics: (1) climate crises may look remote but can strike quickly (2) preparedness is essential and takes years and (3) the cost of preparing is dwarfed by the cost of not preparing' (IMF, 2020). Well before the current pandemic, Martin and Pindyck (2015) called the parallels 'the economics of Scylla and Charybdis'.

Calls to 'build back better' go with the grain of a pre-pandemic shift towards cleaner products and production processes. Our analysis shows how the zero-carbon economy is starting to take hold. The structural challenge for the COVID economic recovery is to maintain this momentum.

Similar to all structural change, creating a post-COVID zero-carbon economy will create both winners and losers. All the countries we analysed have existing strengths and new opportunities in the zero-carbon economy, but many of them also face threats to some currently well-performing sectors. With the notable exception of South Korea and perhaps China and Taiwan, emerging markets appear less well prepared for a zero-carbon recovery than the leading industrialised countries. We identify sectors where clean newcomers could gain market share (such as textiles and chemicals) and sectors where innovating incumbents might prevail (such as automotive).

It is worth emphasising that we can only offer broad indications of potential trends. The ultimate outcomes will depend on the far-sightedness and determination of business leaders, whose actions in turn will be influenced by the business environment in which they operate and by policy interventions that either help or hinder the zero-carbon transition. Creating a favourable business environment for zero-carbon growth is therefore central for a transformative economic recovery. This is a much more structural, long-term challenge than the cyclical need to kick-start economies following the lockdown.

Creating a zero-carbon business environment has many dimensions. Having suitable market conditions to encourage entrepreneurship, innovation, and trade are important enabling conditions for economic success in general. The literature still disagrees on the value of industrial policy to create these conditions. Some authors argue that industrial policy has played only a minor part in recent industrial successes (Pack & Saggi, 2006), while others point to the need to overcome information and other externalities (e.g. Hausmann & Rodrik, 2003).

There is more evidence in support of clean innovation policy. Environmental regulation can boost clean innovation, leading to improved resource efficiency and ultimately higher growth (Porter, 1991; Porter & van der Linde, 1995). Economies of scale and the expertise developed in the domestic market may then boost export opportunities through a home market effect (Hanson & Xiang, 2004; Krugman, 1980). Clean technology support is also justified on the grounds of addressing barriers to low-carbon innovation and breaking out of the world's high-carbon 'lock-in' (Acemoglu et al., 2012; Aghion et al., 2016).

Although this paper has focused on economic rivalry and competitiveness, a zero-carbon recovery has a strong cooperative dimension. Countries that are not at the innovation frontier can foster connections with and learn from the main innovation hubs. They can tie themselves into green supply chains by providing labour, land and other input materials at competitive prices for the manufacture of zero-carbon products. Access to technology may spread through scientific collaboration, trade and technology diffusion, ensuring that the gains from frontier clean innovation are widely diffused.

It is also worth remembering how changes in business competitiveness link to national prosperity. What ultimately matters for prosperity are real incomes and productivity. As the relative demand for zero-carbon products rises globally, the countries with a comparative advantage in them will benefit from improved terms of trade and thus higher real incomes. But other countries benefit, too, if their demand in clean products can be met more cheaply and efficiently by suppliers with a comparative advantage in producing them. This is the basic tenet of green growth. Producers and consumers alike will benefit from a zero-carbon recovery.

Data

The primary data used in this paper are all in the public domain. Patent data are available from PATSTAT: https://www.epo.org/searching-for-patents/business/patstat.html. Trade data are available from COMTRADE: https://comtrade.un.org/data/. Economic output data are available from UNIDO: https://stat.unido.org/. The manipulated GII and RCA data are available from the authors.

Acknowledgements. The authors wish to thank Tilman Altenburg, Alex Bowen, Josh Burke, Raphael Calel, Antoine Dechezleprêtre, Bert de Vries, Ian Golding, Pantelis Koutroumpis, Anna Pegels and Misato Sato for their comments and feedback on an earlier version of the paper. We are grateful to Antoine Dechezleprêtre and Misato Sato for providing us with the patent data.

Financial support. Fankhauser acknowledges financial support from the Grantham Foundation for the Protection of the Environment and the UK Economic and Social Research Council (ESRC) through its support of the Centre for Climate Change Economics and Policy (CCCEP). Srivastav acknowledges funding from the Oxford Martin School Programme on Technological and Economic Change, which is supported by Arrowgrass.

Conflict of interest. None.

Notes

i The global policy response is tracked by the International Monetary Fund at https://www.imf.org/en/Topics/imf-and-covid19/Policy-Responses-to-COVID-19#top.

ii There are patent data for 81 countries and they constitute the reference area for the GII.

iii We have a larger reference area of 175 countries for the RCA. The difference in reference areas between GII and RCA is not problematic methodologically.

iv See https://unstats.un.org/unsd/tradekb/.

References

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The environment and directed technical change. *American Economic Review*, *102*(1), 131–66.

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., & Van Reenen, J. (2016). Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. *Journal of Political Economy*, *124*(1), 1–51.

Allan, J., Donovan, C., Ekins, P., Gambhir, A., Hepburn, C., Robins, N., Reay, D., Shuckburgh, E., & Zenghelis, D. (2020). A net-zero emissions economic recovery from COVID-19. Working Paper 20-01, Smith School of Enterprise and the Environment, Oxford University, April.

Archibugi, D., Howells, J., & Michie, J. (1999). Innovation systems in a global economy. *Technology Analysis & Strategic Management*, *11*(4), 527–539.

Averchenkova, A., & Guzman Luna, S. (2018). Mexico's General Law on Climate Change: Key achievements and challenges ahead. Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science.

Balassa, B. (1965). Trade liberalisation and revealed comparative advantage. *The Manchester School of Economics and Social Studies*, *33*, 99–123

Bell, M., & Albu, M. (1999). Knowledge systems and technological dynamism in industrial clusters in developing countries. *World Development*, *27*(9), 1715–1734.

Bell, M., & Pavitt, K. (1993). Technological accumulation and industrial growth: Contrasts between developed and developing countries. *Industrial and Corporate Change*, *2*(2), 157–210.

Bowen, A., & Fankhauser, S. (2011). The green growth narrative: Paradigm shift or just spin? *Global Environmental Change*, *21*(4), 1157–1159.

Brahmbhatt, M. (2014). Criticizing green stimulus. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(1), 15–21.

Climate Emergency Declaration. (2020). Climate emergency declarations in 1,769 jurisdictions and local governments cover 820 million citizens. https://climateemergencydeclaration.org/climate-emergency-declarations-cover-15-million-citizens/, Accessed 20 September 2020.

Dechezleprêtre, A., Glachant, M., Haščič, I., Johnstone, N., & Ménière, Y. (2011). Invention and transfer of climate change–mitigation technologies: A global analysis. *Review of Environmental Economics and Policy*, *5*(1), 109–130.

EBRD. (2020). *Chapter 4: Green Industrial Policy* (Transition Report 2020). European Bank for Reconstruction and Development, London.

Eskander, S. M., Fankhauser, S., & Setzer, J. (2020). Global Lessons from Climate Change Legislation and Litigation. Working Paper No. w27365. National Bureau of Economic Research, Cambridge MA.

Fankhauser, S., Bowen, A., Calel, R., Dechezleprêtre, A., Grover, D., Rydge, J., & Sato, M. (2013). Who will win the green race? In search of environmental competitiveness and innovation. *Global Environmental Change*, *23*, 902–913.

FTSE Russell. (2018). Investing in the global green economy: Busting common myths. London, May. https://www.ftserussell.com/research/investing-global-green-economy-busting-common-myths.

Green, F., & Stern, N. (2017). China's changing economy: Implications for its carbon dioxide emissions. *Climate Policy*, *17*(4), 423–442.

Griliches, Z. (1990). Patent statistics as economic indicators: A survey. *Journal of Economic Literature*, *28*(4), 1661–1707.

Hanson, G. H., & Xiang, C. (2004). The home market effect and bilateral trade patterns. *American Economic Review*, *94*(4), 1108–1

Hausmann, R., & Hidalgo, C. (2010). The building blocks of economic complexity. *Proceedings of the National Academy of Sciences*, *106*(26), 10570–10575.
Hausmann, R., & Rodrik, D. (2003). Economic development as self-discovery. *Journal of Development Economics*, *72*, 603–633.
Helm, D. (2020). The environmental impacts of the coronavirus. *Environmental & Resource Economics*, *76*, 21–38.
Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J., & Zenghelis, D. (2020). Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change?. *Oxford Review of Economic Policy*, *36*(S1).
Hidalgo, C., Klinger, B., Barabási, A., & Hausmann, R. (2007). The product space conditions and the development of nations. *Science (New York, N.Y.)*, *317*(5837), 482–487.
Howarth, C., Bryant, P., Corner, A., Fankhauser, S., Gouldson, A., Whitmarsh, L., & Willis, R. (2020). Building a social mandate for climate action: Lessons from COVID-19. *Environmental and Resource Economics*, *76*, 1107–1115.
Iapadre, L. P. (2001). Measuring international specialization. *International Advances in Economic Research*, *7*(2), 173–183.
IEA. (2020). Sustainable Recovery. World Energy Outlook Special Report. Paris: International Energy Agency.
IMF. (2020). Greening the recovery, IMF Fiscal Affairs Special Series on Fiscal Policies to Respond to COVID-19, Washington DC.
Johnstone, N., Haščič, I., & Popp, D. (2010). Renewable energy policies and technological innovation: Evidence based on patent counts. *Environmental and Resource Economics*, *45*(1), 133–55.
Jones, R. S., & Yoo, B. (2011). Korea's Green Growth Strategy: Mitigating Climate Change and Developing New Growth Engines. Working Paper No. 798, OECD, Paris.
Kim, S. Y., & Thurbon, E. (2015). Developmental environmentalism: Explaining South Korea's ambitious pursuit of green growth. *Politics & Society*, *43*(2), 213–240.
Krugman, P. (1980). Scale economies, product differentiation, and the pattern of trade. *American Economic Review*, *70*(5), 950–95
Lanjouw, J., & Mody, A. (1996). Innovation and the international diffusion of environmentally responsive technology. *Research Policy*, *25*, 549–71.
Laursen, K. (1998). Revealed Comparative Advantage and the Alternatives as Measures of International Specialisation, Danish Research Unit for Industrial Dynamics, Copenhagen Business School, Copenhagen.
Martin, I. W., & Pindyck, R. S. (2015). Averting catastrophes: The strange economics of Scylla and charybdis. *American Economic Review*, *105*(10), 2947–85.
Mathews, J. A. (2012). Green growth strategies – Korean initiatives. *Futures*, *44* (8), 761–769.
Mealy, P., & Teytelboym, A. (2020). Economic complexity and the green economy. *Research Policy*, 103948.
OECD. (2009). OECD Patent Statistics Manual. Technical Report, Organization for Economic Cooperation and Development, Paris.
OECD. (2008). Eco-Innovation Policies in Mexico, Environment Directorate, Organization for Economic Cooperation and Development, Paris.
Oltra, V., & Saint Jean, M. (2009). Sectoral systems of environmental innovation: An application to the French automotive industry. *Technological Forecasting & Social Change*, *76*, 567–583.
Pack, H., & Saggi, K. (2006). Is there a case for industrial policy? A critical survey. *The World Bank Research Observer*, *21*(2), 267–297.
Perez, C. (2010). Technological revolutions and techno-economic paradigms. *Cambridge Journal of Economics*, *34*, 185–202.
Perez, C. (2019). Transitioning to smart green growth: Lessons from history. In R. Fouquet (ed.), *Handbook on green growth* (pp. 447–463). Edward Elgar Publishing.
Popp, D. (2002). Induced innovation and energy prices. *American Economic Review*, *92*(1), 160–80.
Porter, M. (1991). America's green strategy. *Scientific American*, *264*(4), 96.
Porter, M., & van der Linde, C. (1995). Green and competitive: Ending the stalemate. *Harvard Business Review*, 120–134.
Rammer, C., Gottschalk, S., Peneder, M., Wörter, M., Stucki, T., & Arvanitis, S. (2017). Does energy policy hurt international competitiveness of firms? A comparative study for Germany, Switzerland and Austria. *Energy Policy*, *109*, 154–180.
Scharlemann, J. P., & Laurance, W. F. (2008). How green are biofuels?. *Science (New York, N.Y.)*, *319*(5859), 43–44.
Schwab, K., & Malleret, T. (2020). *COVID 19. The great reset*. World Economic Forum.
Sovacool, B. K., Del Rio, D. F., & Griffiths, S. (2020). Contextualizing the COVID-19 pandemic for a carbon-constrained world: Insights for sustainability transitions, energy justice, and research methodology. *Energy Research & Social Science*, *68*, 101701.
Stern, N. (2011). Raising consumption, maintaining growth and reducing emissions: The objectives and challenges of China's radical change in strategy and its implications for the world economy. *World Economics*, *12*(4), 13–34.
Stern, N., Unsworth, S., Valero, A., Zenghelis, D., Rydge, J., & Robins, N. (2020). Strategy, investment and policy for a strong and sustainable recovery: an action plan. CEP Paper 005, Centre for Economic Performance, London School of Economics, July.
Unsworth, S., Valero, A., Martin, R., & Verhoeven, D. (2020). Seizing sustainable growth opportunities from zero emission passenger vehicles in the UK. Working Paper No. 37. Centre for Economic Performance, London School of Economics.
Zenghelis, D. (2014). In praise of a green stimulus. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(1), 7–14.

Appendix A: Methodology

A.1. Approach

Our methodology is taken from and described in detail in Fankhauser et al. (2013). The focus on future low-carbon competitiveness makes their approach very suitable to study the structural aspects of a zero-carbon recovery.

Besides the interest in COVID 19, we depart from the earlier framework in three ways. First, we provide more recent empirical estimates, extending the original 2005–2007 numbers to the period 2005–2015. Second, manufacturing sectors are analysed at the three-digit level of the ISIC Rev 3.1 classification, while Fankhauser et al. (2013) provide results at the four-digit level. The higher level of aggregation increases the robustness of results and permits the inclusion of additional countries with lower patent numbers: 14 countries, compared to the original eight, including nine emerging markets. Country sectors with fewer than 20 patents in total (green and non-green) are excluded from the analysis. Third, we offer an intuitive new interpretation of our results in terms of SWOT, corroborated by selected examples of country-sector innovation.

The analytical framework tracks how the share of low- and ultimately zero-carbon products and processes evolves across all sectors of the economy. We define our variable of interest, Γ_{is}, as the share of low-carbon output in sector s and country i, G_{is}, relative to total global output (green and non-green) in that sector, $Y_s = \sum_i Y_{is}$. We can further expand Γ_{is} as follows:

$$\Gamma_{is} \equiv \frac{G_{is}}{Y_s} = \frac{G_{is}}{Y_{is}} \times \frac{Y_{is}}{Y_s} \quad (1)$$

The permutation, although self-evident, brings out the two key factors which determine low-carbon output in a country-sector at any one point in time: (i) the share of low-carbon output in total output in the sector, G_{is}/Y_{is} (e.g. the share of electric car sales) and (ii) the sector's global market share, Y_{is}/Y_s (e.g. national versus global growth in the automotive sector).

We explore each of the two factors in turn.

A.2. Tracking zero-carbon conversion

Our chosen indicator for changes in the share of zero-carbon output is low-carbon innovation. The choice is consistent with the view that Schumpeterian 'creative destruction' will be the engine of transformative growth in the long term (Archibugi et al., 1999; Oltra & Saint Jean, 2009; Perez, 2010).

Low-carbon innovation in turn is measured by the number of low-carbon patents in each country and sector. The advantages and limitations of patenting as a measure of innovation have been discussed at length (e.g. Griliches, 1990; OECD, 2009). Although patents are not a complete manifestation of innovation, they are a core measure of innovation *output* that has been used successfully in numerous studies of green innovation (e.g. Dechezleprêtre et al., 2011; Johnstone et al., 2010; Lanjouw & Mody, 1996; Popp, 2002).

Specifically, we use data from the European Patent Office (EPO) on worldwide patenting activity from 2005 to 2015. The EPO classification system includes a code for climate change mitigation patents (the Y02 class of patents), which allows for an easy delineation between high and low-carbon innovation. Patents were allocated to sectors by matching the name of the patent holder to their sector of activity.

We use these data to construct an index of green innovation (GII) of the following form:

$$\mathrm{GII}_{is} = \frac{p_{is}^{G}/p_{is}}{\sum_i p_{is}^{G}/p_{is}} \tag{2}$$

where p_{is}^{G} is the number of low-carbon patents and p_{is} the total number of patents in sector s and country i. The index thus measures the share of low-carbon patenting in a country-sector, compared to the share of low-carbon patenting in that sector over the entire reference area.[ii] The normalisation against broader patenting activity is important to correct for idiosyncrasies in patenting behaviour in particular sectors or countries. However, one side effect is that the scores for large countries, which are a significant part of the denominator, tend to converge towards one.

A.3. Tracking zero-carbon competitiveness

Our chosen indicator to measure zero-carbon competitiveness is current comparative advantage. The choice is consistent with the premise that zero-carbon competitiveness is likely to be derived from existing comparative advantages, skills and production patterns (Hausmann & Hidalgo, 2010; Hidalgo et al., 2007). Comparative advantage evolves slowly as countries diversify into related technologies. This does not preclude market entry and exit at the firm level, since new market entrants will benefit from existing competencies.

A widely used measure of comparative advantage is export share (e.g. Rammer et al., 2017) and specifically the Balassa index of RCA (see Balassa, 1965). There are several variants of the Balassa index, each with its own advantages and disadvantages (Iapadre, 2001; Laursen, 1998). The standard formulation has the following structure:

$$\mathrm{RCA}_{is} = \frac{e_{is}/\sum_s e_{is}}{\sum_i e_{is}/\sum_s \sum_i e_{is}} \tag{3}$$

where e_{is} is the level of exports from sector s in country i. The numerator measures the share of exports in a country-sector, relative to total exports from that country. This is put in proportion to the same ratio (sector exports over total exports) for all countries in the sample.[iii] The focus in the RCA formula is thus on sector exports *relative to* a country's total exports, i.e. on a country's comparative (rather than absolute) advantage.

The RCA index is calculated using trade data for the period from 2005 to 2015 from United Nations International Trade Statistics Database (COMTRADE).[iv] We use RCA to track changes in comparative advantage. The higher the relative share of exports in a country-sector, the higher is its RCA and the more competitive is the sector. A high RCA is an indication of the ability of a country-sector to gain and maintain market share in the future.