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Who will win the green race? In search of environmental competitiveness and innovation[☆]

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ABSTRACT

As the world considers greener forms of economic growth, countries and sectors are beginning to position themselves for the emerging green economy. This paper combines patent data with international trade and output data in order to investigate who the winners of this "green race" might be. The analysis covers 110 manufacturing sectors in eight countries (China, Germany, France, Italy, Japan, South Korea, UK and the US) using date for the period 2005–2007. We identify three success factors for green competitiveness at the sector level: the speed at which sectors convert to green products and processes (measured by green innovation), their ability to gain and maintain market share (measured by existing comparative advantages) and a favourable starting point (measured by current output). We find that the green race is likely to alter the present competitiveness landscape. Many incumbent country-sectors with strong comparative advantages today lag behind in terms of green conversion, suggesting that they could lose their competitive edge. Japan, and to a lesser extent Germany, appear best placed to benefit from the green economy, while other European countries (Italy in particular) could fall behind. However, the green economy is much broader than the few flagship sectors on which the debate tends to focus, and each country has its niches of green competitiveness.

1. Introduction

Policy-makers increasingly place economic growth at the centre of discussions over environmental management. They would like environmental policy to bring much-needed jobs, new technologies and competitiveness to domestic industry, as well as to protect the environment. Creating new market opportunities is an explicit objective of green growth policies in Europe (European Commission, 2012). China is promoting seven strategic industries (including, among others, clean energy, environmental protection and clean cars) that it hopes will place it at the forefront of green growth (Stern, 2010, 2011). South Korea, too, has made green growth a strategic priority (Ministry of Government Legislation, 2010).

This vision is supported by the emerging "green growth" literature. Counterbalancing calls for de-growth (Jackson, 2009; Martínez-Alier et al., 2010), proponents of green growth assert that environmental stewardship is no impediment to economic prosperity, and may in some cases be a spur to growth (Bowen and Fankhauser, 2011; World Bank, 2012; Jacobs, 2013). Yet, the factors that affect the potential of environmental policy to improve competitiveness are poorly understood. And, perhaps as a consequence, there is little evidence about who the winners of the global "green race" might be.

This study contributes both to the conceptual understanding and to the empirical discussion of green competitiveness. We present an analytical framework based on decomposition analysis that can help to structure a discussion that has so far lacked a consistent analytical foundation. The framework identifies three success factors for green competitiveness at the sector level: the speed at which sectors may convert to green products and processes (measured by green innovation), their ability to gain and maintain market share (measured by existing comparative advantages) and a favourable starting point (measured by current output). We apply this framework to 110 manufacturing sectors of eight major economies, based on a large data set that combines patenting activity by over 127,000 firms with international sector-level trade and output data. Our analysis covers China, France, Germany, Italy, Japan, South Korea, the UK and the United States.

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We find that the green race is likely to alter the present competitiveness landscape. Several incumbent country-sectors with strong comparative advantages today lag behind in terms of green conversion, suggesting that they might lose their competitive edge. Manufacturers in Japan, and to a lesser extent Germany, appear best placed to benefit from the green economy, while those in other European countries (Italy in particular) could fall behind. However, the green economy is much broader than the few flagship sectors on which the debate tends to focus, and each country has its niches of green competitiveness.

Our *sector-level* analysis relates to a long-running debate about the link between competitiveness and environmental performance at the *level of firms* (Porter, 1991; Porter and van der Linde, 1995; Reinhardt, 1999; Esty and Winston, 2009). The empirical evidence from the firm-level literature is not always conclusive. For example, Martin et al. (2011) find that climate-friendly management practices are associated with lower energy intensity and higher productivity. Becker and Shadbegian (2009) in contrast find that 'green' manufacturing firms do not systematically outperform 'non-green' manufacturers on indicators such as survival, export growth, employment growth and productivity, although they pay higher wages.

There is also a debate about the role of industrial policy in shaping the green economy. Some authors see a need for industrial policy due to information externalities (e.g. Hausmann and Rodrik, 2003). Others argue that the information constraints on policy-makers are prohibitive and that industrial policy has played only a minor part in recent industrial successes (Pack and Saggi, 2006). What is clear is that business interest in the green economy depends on good and consistent public policy. Sound environmental policies (e.g. a price on carbon) with long-term credibility are essential to correct basic market failures and give environmental services a monetary value (Costantini and Crespi, 2008; Fankhauser, 2012; Kennett and Steenblik, 2005). Without them business interest soon dries up.

We do not aim to add to the industrial policy or innovation debate in this paper, and indeed we would caution against trying to infer too many policy implications from our findings. Our aim is simpler and more descriptive: To add to the understanding of green competitiveness at the sector level, focusing (somewhat narrowly) on manufacturing. This is a question of considerable interest to policy makers, as a series of policy reports and country performance rankings attest (e.g. Ernst and Young, 2008; ECORYS, 2009; Henderson et al., 2013; Pew, 2010; WWF, 2012). However, at the sector-level a rigorous assessment based on a clear analytical framework has so far been lacking. We also assemble a detailed new dataset that can help with further research in this area.

The paper is structured as follows. The next section outlines the analytical framework that underpins our analysis. In Section 3, we present the data and introduce proxies for the three factors we use to assess green competitiveness. Section 4 presents results for the eight countries we consider and some key manufacturing sectors. Section 5 concludes.

2. Understanding green competitiveness

2.1. What is a green economy?

There is an established tradition of measuring the contribution to GDP of the environmental goods and services sector. In the definition of the OECD, environmental goods and services include all activities that measure, prevent, limit, minimise or correct environmental damage (OECD, 1998). Other definitions vary (Steenblik, 2004), as do numerical estimates, but it is clear that according to this delineation the green economy is worth several hundred billion, and perhaps several trillion, US dollars a year globally (EBI, 2012; ECORYS, 2012; BIS, 2011).

Yet, for many of its proponents green growth is about something more radical (Bowen and Fankhauser, 2011; Jacobs, 2013). Green growth advocates do not see environmental management as just another economic sector alongside conventional activity. They argue that the economic changes required to combat problems like climate change are not marginal, as most traditional models suggest, but transformative and system-wide (Perez, 2010; Stern, 2010). The creation of a green economy will therefore affect not just a few sectors but the product mix and production processes of virtually the whole economy.

Consistent with this literature, we interpret green growth as an economy-wide transformation, rather than the expansion of the environmental goods and services sector. We are equally interested in the structural changes within a sector (say, the emergence of low-emissions technology in car manufacturing) as in the expansion of one sector (such as solar panel production) at the expense of another (such as coal mining).

The idea of countries competing for market share in an emerging green economy is rooted in our understanding of the organic, bottom-up dynamics of national and sectoral innovation systems (Archibugi et al., 1999; Dosi et al., 1988; Malebra, 2002). Systems of innovation are distinct networks of public and private institution within countries and sectors that initiate, coordinate, import, modify and diffuse new technologies. Innovation systems may explain why some sectors excel at adapting to and exploiting the opportunities presented by a green economy. Our expectation is that differences across innovation systems will reveal large differences in the responsiveness of sectors and countries to the opportunities in the emerging green economy.

The competitiveness literature suggests that green competitiveness is most likely to be derived from existing comparative advantages, skills and production patterns (Hidalgo et al., 2007; Hausmann and Hidalgo, 2010). For example, Germany developed a comparative advantage in wind turbines on the back of its existing expertise in high-precision machining (Huberty et al., 2011). We therefore treat existing capabilities as a key indicator of future comparative advantage in the green economy. This does not preclude market entry and exit at firm level. The idea of 'creative destruction', where new firms and new ideas drive out the old (Schumpeter, 1942), is central to the type of transformative growth that the green economy discourse espouses (see also Aghion and Howitt, 1998, 2009; Dosi et al., 1988; Malebra, 2002; Oltra and Saint Jean, 2009; Perez, 2002).

Structural change of this scale will create both winners and losers. Some economic activities will be scaled back, and if there are rigidities in relative wages, skills and production techniques, this will lead to a temporary drop in output and employment (Babiker and Eckaus, 2007). At the same time, the rewards could be massive for the winners of the "green race", which obtain a comparative advantage in environmentally benign products and processes.

Although they are used here, terms like "race", "comparative advantage" and "competitiveness" should be interpreted with caution (as famously argued by Krugman, 1994). Firms are competitive if they offer products and services that are in demand in the market place (e.g. because they are cheaper or of superior quality). Countries gain a comparative advantage (and specialise) in areas where they can produce with lower opportunity costs relative to others. But the notion of a race between countries, or competitiveness at the country level, is misleading (Voituriez and Balmer, 2012). What ultimately matters at the national level are real incomes and productivity. The countries that develop a comparative advantage in greener goods and services will benefit from improved terms of trade and thus higher real incomes as policies around the world raise the relative demand for such products. But other countries benefit, too, if the shift in demand towards greener goods and services is met by supply from nations with a comparative advantage in producing them, keeping their relative prices lower than otherwise.

2.2. An analytical framework

To establish who is best placed to succeed in an expanding green economy we start with a hypothetical question: When future statisticians look back, how will they document the transition from the economies of the 2010s to the increasingly green economy of the 2030s and 2040s?

We postulate that future statisticians might use the same analytical tools that today's economists and statisticians use to disentangle the factors that determine a country's energy efficiency, that is, tools such as index number theory and decomposition analysis (e.g. Boyd et al., 1987; Ang and Zhang, 2000; Cornillie and Fankhauser, 2004; Boyd and Roop, 2004; Metcalf, 2008; for a non-energy application, see Antweiler et al., 2011).

They might start with an equation that describes the size of the green economy in country i at time t, G_{it}, as the sum of green output in each sector s, G_{ist}, where G_{ist} is further decomposed as follows:

$$G_{it} = \sum_s G_{ist} = \sum_s g_{ist} \times m_{ist} \times Y_{st} \tag{1}$$

Y_{st} denotes global output from sector s at time t, and is defined as the sum of country-level outputs, $Y_{st} \equiv \sum_i Y_{ist}$. Furthermore, $g_{ist} \equiv G_{ist}/Y_{ist}$ is the green share in the economic output of sector s in country i, and $m_{ist} \equiv Y_{ist}/Y_{st}$ is the international market share of country i in sector s.

Future statisticians would then proceed to differentiate this equation with respect to time. They may also undertake a series of permutations to express change in discrete, rather than continuous, time (see e.g. Boyd et al., 1987; Metcalf, 2008). This would allow them to document how the size of the green economy changes, time period by time period, as a result of changes in the three constituent elements of Eq. (1), that is, green conversion (changes in the share of green output relative to total sector output, g_{ist}); changes in market share, m_{ist}, and changes in the size of a sector worldwide, Y_{st}.

Before approaching this task, we make two simplifications. First we focus on the green output potential of individual country-sectors, G_{ist}, rather than the size of the entire economy, G_{it}. This allows us to ignore the sector summations, and we can simplify the notation by dropping sector and country subscripts.

Second we move the total sector size, Y_{st}, to the left-hand side of the equation. This creates a new left-hand variable $\Gamma_t \equiv G_{ist}/Y_{st}$, which measures green production in a sector and country relative to global sector size.

Making these adjustments, differentiating the simplified equation with respect to time and integrating back, we get the following expression for relative green production at a future time T:

$$\Gamma_T = \int_0^T \frac{\partial g_t}{\partial t} \times m_t d_t + \int_0^T \frac{\partial m_t}{\partial t} \times g_t d_t + \Gamma_0 \tag{2}$$

Eq. (2) tells us that future green output in a country-sector, relative to global sector output, depends on three trends:

- *Green conversion*, that is, the speed with which the green segment of the market will grow within a country-sector (e.g. the rise in renewable electricity at the expense of conventional power generation within the electricity sector).
- *Change in the market share* of a sector, that is, the ability of a sector to outpace the overall rate of growth (e.g. growth in electricity production as clean electricity replaces fossil fuels in heating and transport).
- The importance of *green production at the outset* (i.e. renewable power generation today, relative to global power generation)

Eq. (2) also makes clear that the conversion process does not have to be smooth. It is the integral over a dynamic process that may include ups and downs. We know from economic history, for example, that there may be rebound effects and competing innovation in non-green products and processes (Fouquet, 2010). This is sometimes called the "sailing ship effect" after the incumbent technology threatened by innovation where the effect was first observed (Graham, 1956).

Nevertheless, the three factors above, in all their complexity, are the drivers we need to understand and estimate if we want to assess the readiness of country-sectors (and for that matter, firms) to compete in an increasingly green economy. The first two together indicate the *green growth potential* in a sector and will be of particular interest below. The third factor determines the starting point, but also the relative importance of a sector in the global economy.

3. Measuring green competitiveness

When documenting the emergence of the green economy, future statisticians will be able to track the three trends of Eq. (2) *ex post* and measure their relative importance using actual data. In contrast, our analysis is forward-looking. The first two components of Eq. (2) in particular cannot yet be measured in the way future statisticians will be able to. The third component, green production today, should in principle be observable, but it turns out that the data to measure it meaningfully are poor.

We therefore require a set of lead indicators that let us predict the three future trends *ex ante*. In other words, we are looking for indicators of country-sector performance today that are correlated with leadership in the green economy tomorrow, and can serve as proxies for, future green conversion, future market share and green production today. Although the conversion processes we anticipate are dynamic (as Eq. (2) makes clear), the lead indicators associated with them can be static, and they will necessarily be imperfect. No indicator can predict accurately a complex dynamic process several decades into the future. Nevertheless, the aim is to find the most credible such indicators at the level of country-sectors.

3.1. Green conversion

The most promising indicator for green conversion, that is, the speed at which green output will replace conventional products and processes, is green innovation. The focus on innovation, rather than investment, is consistent with the view that "creative destruction" is the engine of transformative growth (Archibugi et al., 1999; Oltra and Saint Jean 2009; Perez, 2002). Innovation alters products and production processes much more profoundly than does investment, although the two processes are obviously linked. While investment determines the future capital stock, innovation determines how radically different that capital stock will be. More broadly, there is a well-documented link between innovation, productivity and economic growth (Aghion and Howitt, 1998, 2009; Griliches, 1979; Temple, 1999), and between innovation, industrial dynamics and industry evolution (Dosi et al., 1988; Malebra, 2007, 2002).

We calculate for each country-sector an index of green innovation activity, which measures the ratio of green patents to total (green plus non-green) patenting activity. The advantages and limitations of patenting as a measure of innovation have been discussed at length (see Griliches, 1990; and OECD, 2009, for a recent overview). While patents are not a complete manifestation of innovation, they are a core output measure that features prominently even in complex assessments of innovation performance (for example, Dutta, 2012; Hollanders and Es-Sadki, 2013).

A key advantage for our purpose is that patent data are available at a highly disaggregated level. This allows us to map innovations in clean technologies, such as renewable energy technologies, electric vehicles, energy-efficient cements, insulation devices, and so on. R&D expenditures cannot be disaggregated by type of innovation in this way. Further, R&D spending is typically only reported for large firms, whereas our data are available for all patent holders, including small and medium-sized enterprises. Patent data have been used successfully in numerous studies of green innovation (for example, Dechezleprêtre et al., 2011; Johnstone et al., 2010; Lanjouw and Mody, 1996; Popp, 2002).

An important limitation is that possessing a patent does not imply that the owner will actually use the technology and incorporate it into new products. Yet the high expense of patenting deters the patenting of technologies that are unlikely to be deployed. Filing a patent costs around €5000 in Japan, €10,000 in the US and €30,000 at the European Patent Office (Roland Berger, 2005). Inventors are therefore unlikely to apply for patent protection unless they are relatively certain of the potential market value for the technology. In the absence of information on market shares of green technology-based products, we use patents as a second-best indicator of green conversion.

Our Green Innovation Index (GII) takes the following form, which is similar to Waltz and Eichhammer (2012). For a broader discussion of innovation indices see Grupp (1994):

$$\mathrm{GII}_{is} = \frac{p_{is}^{G}/p_{is}}{\sum_i p_{is}^{G}/p_{is}} \tag{3}$$

where p_{is}^{G} is the number of green patents and p_{is} the total number of patents in sector s and country i. The index thus measures the share of green patenting in a particular country-sector, compared to green patenting in that sector over the entire reference area (that is, the eight case study countries). The normalisation against broader patenting activity is important to correct for idiosyncrasies in patenting behaviour in particular sectors or countries. Indeed, evidence shows that the propensity to use patent differs widely across sectors (Cohen et al., 2000).

The higher the GII for a sector and country, the higher the share of green innovation in that sector, compared with other countries, and the more rapid (we conjecture) the conversion from conventional to green production.

3.2. Change in market share

Drawing on Hidalgo et al. (2007) and Hausmann and Hidalgo (2010), our conjecture is that the future market share of a country in a particular sector is related to its comparative advantage today. Sectors with a competitive edge today are more likely (but not certain) to be successful in the future. Despite its basis in the competitiveness literature, this is a strong assumption in the context of a deep structural transformation.

A widely used way to measure comparative advantage is the Balassa index (Balassa, 1965). The Balassa index measures the revealed comparative advantage (RCA) of a country-sector on the world market by calculating its relative export share. There are several variants of the index, each with its own advantages and disadvantages (Iapadre, 2001; Laursen, 1998). We use the standard formulation, which has the following structure (see also Welfens et al., 2010 for a sustainability application of RCA-style indicators):

$$\mathrm{RCA}_{is} = \frac{e_{is}/\sum_s e_{is}}{\sum_i e_{is}/\sum_s \sum_i e_{is}} \tag{4}$$

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. Unlike equation (3), which measures green innovation in absolute terms, the focus in the RCA formula is on sector exports *relative to* a country's total exports, i.e. on a country's comparative (rather than absolute) advantage. The higher the relative share of exports in a country-sector, the higher is its RCA and the more competitive is the sector.

This indicator offers a first indication of a particular country-sector's ability to gain and maintain market share in the future, although there are clear limits to using past shares as a predictor of future market shares in the presence of technology diffusion and major transformations driven by green innovations. Another drawback of the RCA is that it excludes sectors in which there is no international trade, such as some services.

3.3. Green production at the outset

The main way of measuring green economic output to date has been to identify at a high level of disaggregation (e.g. five- and six-digit level) the sectors whose activities are deemed to contribute to environmental protection and aggregate their output into a single value for the green economy (OECD, 1998; BIS, 2011). This approach tends to categorise sectors dichotomously as either 'environmental' or 'non-environmental', rather than assessing more broadly the share of green production in all sectors of the economy. A study that does the latter is HSBC (2009), which calculates the green revenues earned by the world's listed companies. The HSBC indicator confirms that much of the green revenue does not accrue in explicitly green sectors, but may, for example, concern the wind turbine division of an engineering firm or the biofuel activities of oil companies.

To assess the readiness of individual sectors for the green economy, we need a measure of the starting position for *every sector* and not just for those that have been defined as 'green' by today's standards. To this end we use total sector output as a proxy for total sector green output. A country-sector with a high level of total output is assumed to have a proportionally high level of green output therein. Naturally the strength of the relationship between total and green output varies across sectors and, with green conversion, will change in future. Yet total output offers a reliable, empirically measurable starting point that is consistent with our measure of initial comparative advantage (based on exports) and our rate-of-conversion measure based on green patenting. The level of green output denotes the relative importance of a sector within a country, or the proportion of output within a sector globally that is attributable to a country.

4. Empirical evidence

We next turn to the empirical analysis of the three key factors that predict competitive success in the green economy. According to the analytical model (Eq. (2)), the three factors are additive and could in principle be combined into a single indicator of competitiveness in the green economy. We are not doing this and instead consider the three factors separately. Their interplay is discussed in qualitative terms. The additive structure of Eq. (2) only holds for accurate *ex post* data and not strictly for the *ex ante* proxies we use.

The unit of analysis in our dataset is the country-sector. We consider 110 manufacturing sectors at the four-digit industry level (ISIC Rev. 3 codes 1511-3699, see Annex) in eight countries (China, France, Germany, Italy, Japan, South Korea, US and UK). All eight countries have large, globally competitive manufacturing bases, which offer scope for comparison between country-sectors. For 38 sectors output data were not available (6 in China, 4 in France, 7 in Germany, 3 in Italy, 6 in Japan, 1 in the UK and 11 in the US) and these are excluded from output-related statistics.

The 110 sectors in our sample play different roles in today's economy with respect to the environment and its protection. The sample includes sectors that cause most environmental damage during production, such as pulp, paper and paperboard. It includes sectors whose output causes most environmental damage at the consumption stage, such as motor vehicles, and sectors whose output may cause most damage in the final disposal stage, like processing of nuclear fuel. The sample also includes sectors which may or may not be relatively benign in their own environmental footprint, but which have the potential to contribute to the greening of other sectors. One such sector is electricity distribution and control apparatus, which holds the key to smarter electricity grids.

The empirical data come from a number of sources. Patent data are taken from the Orbis database, maintained by Bureau Van Dijk. The Orbis database records the patent portfolio of over 500,000 companies worldwide. The 4-digit sector classification of the patent holders is also available, which allows us to match individual patents to economic sectors. In order to identify green patents, we use the environment-related patent classification developed by the European Patent Office (EPO) and the OECD. In particular, we use the recently developed Y02 class from the European Classification System (ECLA), which covers patents related to '*technologies or applications for mitigation or adaptation against climate change*' (see Veefkind et al., 2012, for more information on the Y02 class; the list of environment-related patent classification codes is available from http:\\www.oecd.org/environment/innovation). The RCA indicator was calculated using the UN Commodity Trade Statistics (ComTrade) database, while data on current output come from the UN's INDSTAT4 industrial statistics database.

For each indicator, we took averages over several years to smooth out year-on-year fluctuations. The base period is the mean of the years 2005–2007, except current economic activity in China, which is for 2004/05. This has the advantage of avoiding the cyclical effects of the post-2007 economic crisis but the disadvantage of ignoring the latest structural trends in rapidly developing countries like China. In selected sectors, the empirical analysis is complemented by a descriptive analysis based on conversations with sector and country specialists.

4.1. Basic statistics

We start with some basic aggregate statistics to gain an initial sense for the green competitiveness of each country. Table 1 shows a considerable degree of homogeneity with respect to revealed comparative advantage (RCA), which should not surprise in a sample of leading export nations. However, there is a clear leader in green innovation (GII, our measure of green conversion), where Japan has the strongest scores for most indicators.

Japan is the only country with a median green innovation index that is greater than one. It has 61 sectors with above-average green innovation, the highest number of any country by some distance. These sectors account for two-thirds of Japan's manufacturing output, compared with 20–40% elsewhere. Japan also has the deepest level of green innovation in its 15 largest manufacturing sectors. Japan's leading position in green manufacturing appears to be long-lasting and was already observed in some very early studies on the green race in the 1990s (Voituriez and Balmer, 2012). Some industry experts attribute this to Japan's "patenting culture" – patent numbers is or has been an explicit performance indicator at companies like Mitsubishi Heavy Industries, for example – but the GII indicator corrects for such country-level differences by focusing on the *green share* in patents within a country.

Among the European countries considered, Germany has the strongest record on green innovation, second only to Japan's. In contrast, the other European countries appear to fall behind. Italy in particular has the poorest record of all eight countries, but there are also some alarming results for the UK, and to a lesser extent France. France, Italy and the UK are the only countries where the median green innovation score is below the median RCA, implying an overall innovation performance that is worse than the current competitive position. The three countries also have the lowest number of sectors with competitive green innovation scores (GII > 1) and most sectors without any green innovation at all.

For the remaining countries, the picture is mixed, although according to our data China's innovation record is also quite patchy. This is at odds with the ambitions expressed in China's latest five-year plan (Stern, 2010), and we should expect China's performance to improve as the objectives of the five-year plan are implemented.

4.2. Results by country-sector

The picture becomes more nuanced as we delve deeper into the green performance of individual country-sectors. An instructive way of presenting country-sector data is through scatter diagrams, such as those in Figs. 1 and 2, which plot revealed comparative advantage (RCA) on one axis and green innovation (GII) on the other. The importance of each sector at the outset (its share in

Table 1
Aggregate indicators of green competitiveness.

	China	France	Germany	Italy	Japan	S. Korea	UK	USA
Median RCA	0.7	1.0	0.9	0.9	0.5	0.3	0.7	0.8
Median GII	0.7	0.6	0.9	0.4	1.1	0.9	0.4	1.0
Number of sectors with GII > 1	33	31	44	24	61	40	29	45
Median RCA of sectors with GII > 1	0.7	1.0	1.0	1.1	0.6	0.5	0.8	0.9
Output in sectors with GII > 1 (% of total)[a]	25%	34%	40%	18%	65%	29%	26%	37%
Number of sectors with GII = 0	30	42	21	43	11	22	52	16
Median RCA of sectors with GII = 0	1.0	0.9	0.5	0.9	0.2	0.1	0.5	0.6
Output in with GII = 0 (% of total)[a]	9%	17%	4%	30%	3%	3%	24%	7%
Number of sectors with RCA > 1	42	55	48	51	36	22	31	40
Median GII of sectors with RCA > 1	0.4	0.6	0.9	0.4	1.1	0.9	1.0	1.0
Output in sectors with RCA > 1 (% of total)[a]	44%	56%	56%	51%	47%	46%	32%	55%

[a] Excluding sectors for which output data are missing.

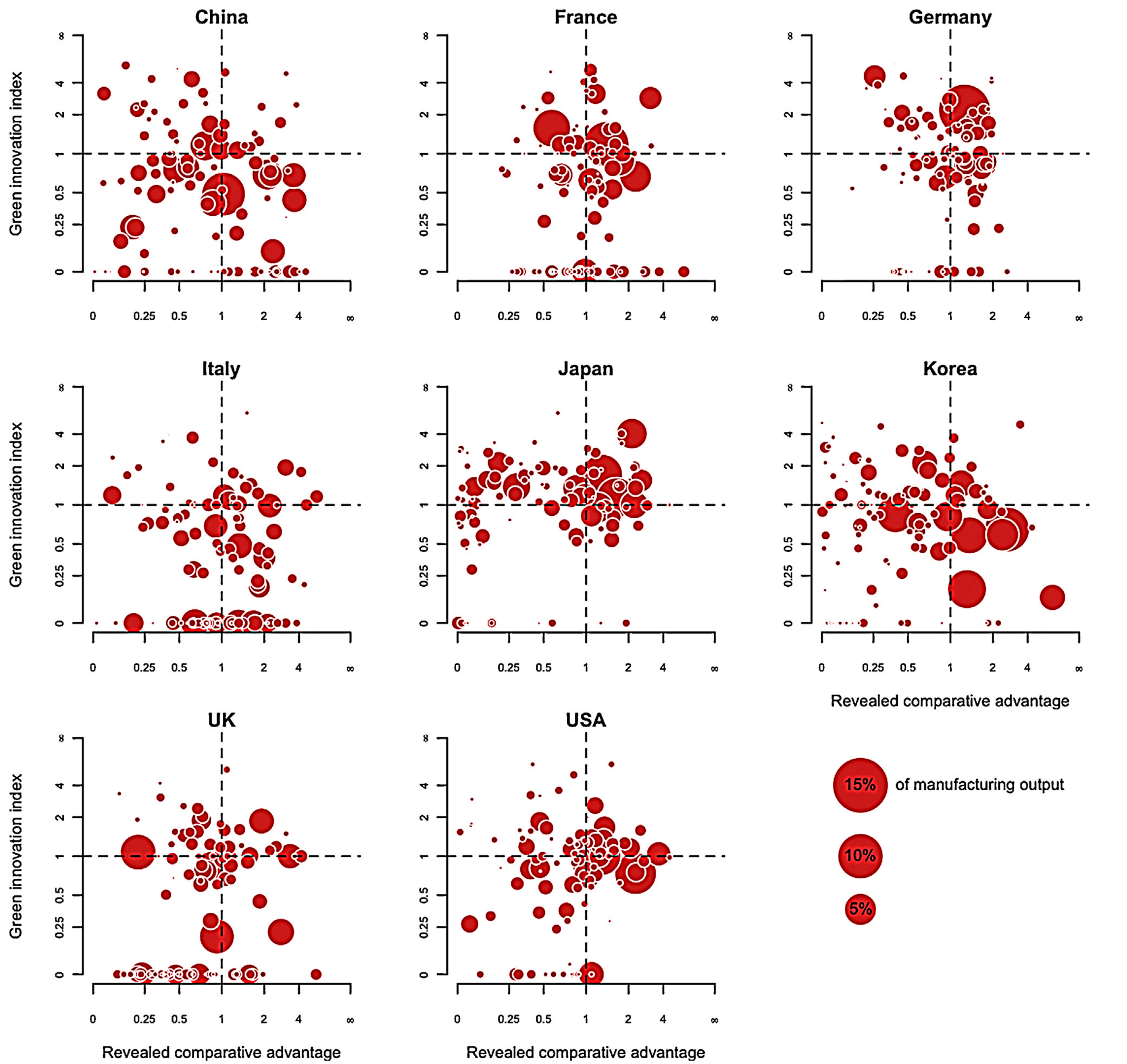

Fig. 1. Potential areas of green competitiveness by country. *Note.* For presentational purposes, the scales for both Revealed Comparative Advantage (*x*-axis) and the Green Innovation Index (*y*-axis) were adjusted to make the distributions (which are right-skewed) appear symmetric. Excludes 38 country-sectors for which output data are missing.

current manufacturing output) is represented by the size of the bubbles.

For both the RCA and the GII, scores between zero and one indicate a below-average performance. The sample average across the eight countries is one, and scores greater than one signify above-average performance. Green competitiveness thus increases as we move to the top and right of the charts.

Fig. 1 includes all 880 country-sectors. It shows green innovation and areas of comparative advantage over a diverse mix of activities that is much broader than the keystone sectors typically associated with green growth (i.e. clean energy, clean cars and resource efficiency). The wide range of green innovation confirms that green growth concerns most, if not all, parts of a modern economy. To illustrate the point, the top three sectors in green innovation in each country include areas such as general purpose machinery (China, Italy, USA), electrical equipment (Korea) and hand tools/general hardware (France, Germany, Japan, UK, USA), as well as in keystone sectors such as electricity distribution (which features in all countries except Korea). Similarly, countries' comparative advantages are in areas such as toys (China), wine (France), motorcycles (Japan) and distilling (UK), although strategic sectors feature in Korea (shipbuilding) and the US (aircraft manufacture, weapons). Italy's strong comparative advantage in machinery for metallurgy is also of note, given that much of the innovation in the strategic steel sector takes place at the leading plant-makers.

Nevertheless, it is instructive to look at the most important sectors of the economy in more detail. Fig. 2 therefore replicates the scatter plots for the 15 biggest sectors in each country by output. Typically, the top 15 sectors account for around 50% of manufacturing output.

Both sets of scatter plots (Figs. 1 and 2) suggest that there is only a weak connection between green innovation and comparative advantage. Over the full sample, the correlation is mildly positive

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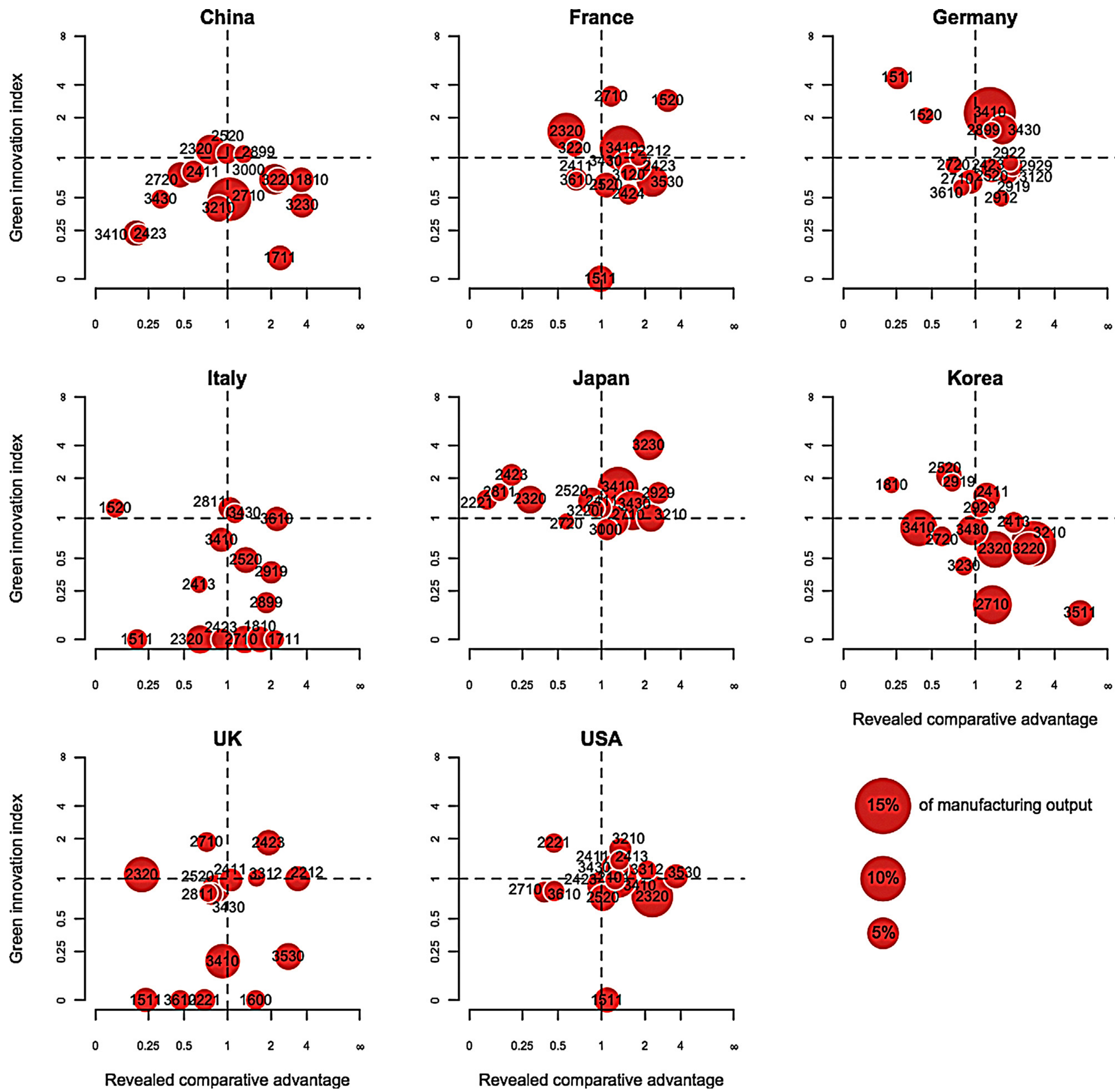

Fig. 2. Potential areas of green competitiveness, 15 biggest sectors only. *Note*. For presentational purposes, the scales for both Revealed Comparative Advantage (*x*-axis) and the Green Innovation Index (*y*-axis) were adjusted to make the distributions (which are right-skewed) appear symmetric. The sector labels are explained in the Annex.

in most countries, that is, green innovation is somewhat stronger in areas of current comparative advantage. However, in two countries, China and Italy, it is negative.

The weak correlation suggests that the green race is likely to alter the competitiveness landscape. The leading country-sectors of today may not be the dominant producers in the green economy.

Particularly at risk are the country-sectors located in the bottom-right quadrants of the scatter plots. They currently enjoy a strong comparative advantage (high RCA score), but are not leading on green conversion (low GII score) and could over time lose their competitive edge. Prominent incumbent sectors in this category include pharmaceuticals in France, plastics in Italy and chemicals in the UK. More generally, we observe a low level of green innovation among the largest leading sectors in China, Italy, Korea and to a lesser extent the UK (Fig. 2).

However, it is difficult to draw general conclusions. Aircraft manufacture in France and the UK both fall into the bottom-right quadrant, but industry experts feel the green race between Europe and the US, the other leading manufacturer, is still neck-and-neck. Similarly, iron and steel in China, another country-sector in the bottom-right quadrant, should be protected by a strong domestic market as long as China's construction boom continues. Korea's leading steel maker, Posco, is known for its ability to adopt innovations quickly and implement them at scale. This skill is not reflected in our GII score.

Another group that could struggle in the green economy is the surprisingly large number of country-sectors with a GII score of zero. These are sectors that show no evidence of green conversion, even though there is green innovation at the international level. In France, Italy and the UK between 40 and 50 sectors (out of 110) fall into this category (Table 1 above). They are important economic activities, which account for 30% of manufacturing output in Italy, 24% in the UK and 17% in France. (Note that sectors without any green innovation anywhere in the sample were assigned a value of 1 in all countries).

The GII = 0 group includes areas where green patents are rare even at the global level, including several agribusiness sectors, but it also covers sectors where there is considerable green innovation internationally, and which are of strategic importance in a green economy. Examples include steam generators (no green innovation in any country except Germany and France), nuclear fuel processing (no country except France), pulp and paper (nothing in France, Italy, UK), steel (Italy), batteries (UK), cement (UK) and engines and turbines (Korea).

The country-sectors most likely to replace complacent incumbents are those located in the top-left quadrants of the scatter plots. These country-sectors do not currently enjoy a comparative advantage (low RCA score), but could break into the market on the back of their strong green innovation record (high GII score). Refined petroleum products might see this shift, with France, Japan and the UK all outperforming Korea and the US, which have the highest RCA scores, on green innovation. However, the refining sector as a whole could lose in economic importance as the world moves away from fossil fuels as a source of energy (Fankhauser, 2012).

The areas of particular promise in the green economy are those located in the top-right quadrants of the scatter plots, since they exhibit comparative strength in both RCA and GII. The full list (shown in Fig. 1) is an eclectic and diverse mix of 115 country-sectors (i.e. about 13% of the sample), which reflect the breadth of the green economy. However, among the top 15 sectors by output we find many of the key strategic sectors of the green economy (Fig. 2 and Table 2). First and foremost are motor vehicles, which feature on the French, German and Japanese lists (and, through car parts and accessories, the US one). The list also includes iron and steel (France) and aircraft manufacture (USA), as well as areas of traditional strength in countries like the UK (pharmaceuticals) and Japan (electronic goods).

Table 2
Top 15 sectors (by output) with comparative advantage and green innovation scores greater than one.

	GII score	RCA score	Output (% of sample)
China			
Other fabricated metal products	1.1	1.0	1.7%
France			
Basic iron and steel	3.1	1.1	2.2%
Dairy products	2.8	3.0	2.6%
Motor vehicles	1.2	1.4	9.8%
Germany			
Motor vehicles	2.2	1.2	13.0%
Parts/accessories for automobiles	1.6	1.5	4.3%
Other fabricated metal products	1.6	1.3	1.4%
Italy			
Structural metal products	1.2	1.0	2.6%
Parts/accessories for automobiles	1.1	1.1	1.9%
Japan			
TV and radio receivers, assoc. goods	4.0	2.1	4.6%
Motor vehicles	1.7	1.3	8.0%
Other special purpose machinery	1.5	2.5	2.5%
Parts/accessories for automobiles	1.1	1.6	7.5%
Electronic valves, tubes, etc.	1.0	2.2	3.8%
South Korea			
Basic chemicals, except fertilizer	1.4	1.2	3.6%
Other special purpose machinery	1.2	1.1	1.8%
UK			
Pharmaceuticals, medicinal chemicals, etc.	1.8	1.9	3.3%
Measuring/testing/navigating appliances, etc.	1.0	1.6	1.6%
USA			
Electronic valves, tubes, etc.	1.6	1.3	2.5%
Plastics in primary forms, synthetic rubbers	1.4	1.3	1.8%
Basic chemicals, except fertilizer	1.2	1.2	3.4%
Parts/accessories for automobiles	1.2	1.3	2.7%
Measuring/testing/navigating appliances, etc.	1.2	2.1	1.9%
Air craft and spacecraft	1.0	3.6	2.9%

Note. All country-sectors with a score of 1.0 are rounded down. Country-sectors with a rounded-up score of 1.0 are not included.

4.3. Results for selected sectors

Our data can also be used to show which countries enjoy a green competitive advantage within specific manufacturing sectors. While the green economy is diverse, there are several strategic sectors whose transformation is central to the creation of a green economy. In Fig. 3, we explore eight of them.

The areas we study include industrial processes, which need to become cleaner and more resource efficient (e.g. iron and steel); sectors that are important for energy efficiency, both on the demand side (domestic appliances) and the supply side (electricity distribution systems); the supply chain for electricity generation and other industrial processes (steam generators; engines and turbines; electric motors and transformers); and car manufacturing, both directly (motor vehicles) and further up the supply chain (accumulators/primary cells/batteries, where progress is needed for electric cars).

The innovation literature shows marked differences in the market structure and organisation of innovation activity between sectors (Malebra, 2007). Some sectors are characterised by structural stability and innovative activity is concentrated in a few incumbent firms. In other sectors, innovation is dynamic and turbulent, with frequent market entry and innovation activity across a wide population of firms.

We observe some of these patterns in the eight sectors of Fig. 3. In two sectors, engines and turbines and motor vehicles, green innovation is driven by the leading country-sectors. There is a clear positive link between green conversion and comparative advantage. In a further two sectors, domestic appliances and accumulators/primary cells/batteries, there is little difference across countries in terms of green innovation.

In these four sectors, the current competitive landscape may prevail. In the case of motor vehicles, car manufacturers in France (e.g. Renault) and Japan (e.g. Toyota) have been at the forefront of electric and hybrid car developments, while German manufacturers have pushed conventional technologies. Among the other countries, recently tightened emissions standards in the US might trigger more green innovation in the important American market. The UK has traditionally specialised in high-end vehicles with high emission factors (the successful Mini apart), but Jaguar Land Rover, the main producer, has now started to lower emissions in some models. Newcomers like China sometimes see green technology as a way of breaking into this highly competitive market, but so far the data do not bear this out.

In iron and steel and for steam generators, there is little variation in comparative advantage, but there are marked differences in green innovation. Especially intriguing is the dichotomy in steam generators, where green innovation is concentrated in just two countries, Germany and France. The absence of Japanese innovation in particular is surprising, given the record of companies such as Mitsubishi Heavy Industries and Kawasaki Heavy Industries. It is possible that their innovation

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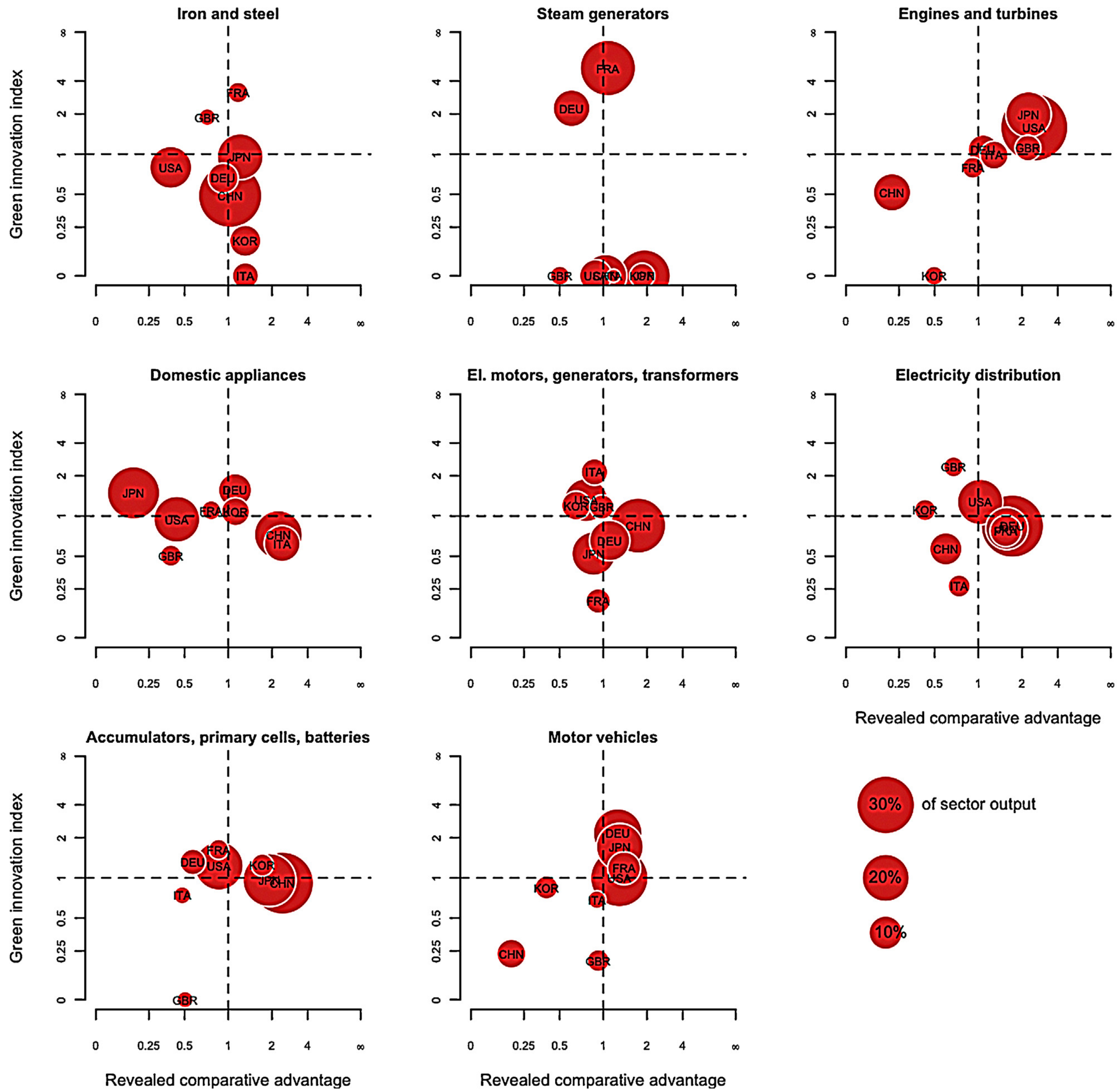

Fig. 3. Green competitiveness in selected sectors. *Note*. For presentational purposes, the scale for both Revealed Comparative Advantage (*x*-axis) and the Green Innovation Index (*y*-axis) was adjusted to make the distributions (which are right-skewed) appear symmetric. The country labels are: CHN = China; DEU = Germany; FRA = France; GBR = United Kingdom; ITA = Italy; JPN = Japan; KOR = South Korea; USA = United States of America.

activities were allocated to other sectors, such as engines and turbines.

In iron and steel, two relatively small producers, France and the UK, are leading the field. This is unlikely to alter the competitive landscape in the long run, however, which is driven largely by factors such as labour and energy costs. In the case of France, the high GII ratio reflects a substantial research presence in the country by big international producers like Arcelor Mittal. The UK position may be related to leadership in building-related steel design, an important area for innovation, but one that may require stronger building regulations to fulfil its potential. It is also worth remembering that our analysis is omitting important steel producers such as Russia and Ukraine. Their success is based primarily on good access to raw materials, rather than innovation.

One interesting pattern in the remaining two sectors (electricity distribution and electric motors/generators/transformers) is the position of Korea and surprisingly also the UK and the US, which are mid-ranking in terms of comparative advantage, but strong on green innovation. If this persists they might be able to catch up with the current leaders.

Overall, all eight countries have areas of promise, but also clear weaknesses, in the strategic sectors. The relatively weak position of China reflects a manufacturing industry that during our 2005–07 snap-shot was heavily dependent on low and mid-level technologies, combined with low labour cost. China experts believe that this is already starting to change. Korea's strengths are on batteries, but also electric motors/generators/transformers and maybe electricity distribution. Japan and the US continue to lead on engines and turbines. Germany will be satisfied with the strong competitive position of its export industry, including an automotive sector that accounts for 13% of manufacturing output. For France, there might be opportunities in steam generators, motor vehicles and perhaps iron and steel, three areas where it has prominent local champions. Italy has a mixed record overall, but

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could be well positioned in domestic appliances and electric motors/generators/transformers. The UK may have opportunities in engines and turbines, where it has a strong base around Rolls Royce, and perhaps electricity distribution. However, Britain performs poorly on steam generators, domestic appliances and (for the time being) motor vehicles.

5. Conclusions

This paper explores the question of green competitiveness, broadly defined. It is important to recognise that green growth would "lift all the boats". Producers and consumers alike would benefit from an economy that is low-carbon, climate-resilient, resource-efficient and biodiverse – the key attributes associated with green growth (Bowen and Fankhauser, 2011). Yet policy makers are also interested to know which countries and sectors might particularly thrive in the green economy. This is relatively new research with few methodological or empirical precedents to draw on in the peer-reviewed literature. (There is more in the grey literature.)

The paper offers preliminary conclusions along three lines. First, in terms of substantive results – the question raised in the paper's title – we conclude that each of the eight countries we study has areas of green competitiveness. They also appear to have areas of weakness, and it is likely that the green race could change the competitive landscape. In some areas the incumbent country-sectors lead the green race, such as motor vehicles and engines and turbines. But in many others the countries that currently enjoy a comparative advantage are not the leading green innovators. Some of them could lose their competitive edge. These strengths and weaknesses are reflective at least in part of the distinct institutional networks and endowments that make up the innovation systems of a country-sector.

The manufacturing sectors of Japan and to a lesser extent Germany seem best positioned to take advantage of the green shake-up. Italy's manufacturing sector has the worst statistics and could fall behind in the green race. There are also question marks (based on our 2005–07 snapshot) about China. In the UK green innovation is concentrated, perhaps strategically, in the energy intensive industries.

We find that the green economy is much broader than the few flagship sectors (e.g. clean energy and clean cars) on which the debate tends to focus. These are undeniably important (Fankhauser, 2012), but there are areas of green entrepreneurship and innovation across the manufacturing sector, including in areas such as machinery and consumer goods and on important issues like resource efficiency and waste management.

The second set of conclusions concerns policy. We have not analysed which policies are best suited to help countries or sectors win the green race. However, it is clear that public policy is important. A key challenge for the green economy is to overcome persistent market failures (e.g. on innovation) and externalities (e.g. pricing the environment), which requires well-designed and consistent public policy intervention. Business decisions on investment and R&D in particular respond to such policy signals. However, a detailed analysis of green industrial policies – and their interplay with other factors such as energy costs – is beyond the scope of this paper.

What we can observe is that the countries in our sample have not been particularly strategic in their green growth strategies. There is little evidence that they are promoting green innovation specifically in their areas of comparative advantage, thus bringing together the two main ingredients for green growth. The correlation between green innovation and current comparative advantage is weak. However, a more detailed analysis at the sector level would be required to understand these trends fully.

The third set of conclusions concern methodology. We have put forward an analytical framework, based on decomposition analysis, which we believe is well suited to assess green competitiveness and the potential for green growth. In fact, the framework is suited to analyse structural transformations of any kind, and may have applications in other areas such as biotechnology. It also offers a basic structure for simulation models of the green economy.

The framework highlights the need for green conversion (through investment and innovation) in all sectors of the economy, and not just the environmental goods and services sector. It also emphasises the need to build on current comparative advantage to develop and maintain market share.

We are on less solid ground when it comes to the proxies used to measure these key factors. They are imperfect on several accounts. There are limits to the availability of data, including on the size of the green economy today. There are questions marks about how accurately green patenting (our measure of innovation) reflects the complex dynamics of green innovation, and how well the place of patent registration pinpoints the actual location of innovative activity (particularly for multinational companies). Similarly, our measure of comparative advantage, the Balassa index, is both too narrow (i.e. limited to traded sectors) and too broad (i.e. covering both traditional and green comparative advantage).

In terms of future research, it would be good to have a better empirical understanding of how our indicators of green innovation and comparative advantage actually contribute to growth. Over time, this will become possible, but at the moment it is still hard. Given that we are studying a structural transformation, past trends are only of limited use. A fruitful area for future research would be to investigate which sector-level institutional forms and interactions underpin the strongest and weakest green conversion rates observed across sectors in our investigation.

The scope of our analysis leaves important omissions. The eight countries we study account for almost two-thirds of global economic output, but data constraints meant we had to leave out many important economies, both present and emerging. Also for data reasons the focus has been on manufacturing. This is too narrow. Modern economies are predominantly service-oriented, and there are considerable green opportunities in sectors such as finance, consulting, engineering, architecture and education. In Europe, at least, the green growth discussion has focused heavily on manufacturing, but there are good reasons to believe that the green economy will be a service economy.

The processes that drive green competitiveness are inherently unpredictable. The leaders and laggards that we have identified in the global green race today could change rapidly in the medium and long term future. Our hope is that the analytical framework laid out here will be useful for measuring and understanding this competitive process, however the race plays out.

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AnnexList of sectors

1511	Processing/preserving of meat	2696	Cutting, shaping and finishing of stone
1512	Processing/preserving of fish	2699	Other non-metallic mineral products n.e.c.
1514	Vegetable and animal oils and fats	2710	Basic iron and steel
1520	Dairy products	2720	Basic precious and non-ferrous metals
1532	Starches and starch products	2811	Structural metal products
1551	Distilling, rectifying and blending of spirits	2812	Tanks, reservoirs and containers of metal
1552	Wines	2813	Steam generators
1554	Soft drinks; mineral waters	2893	Cutlery, hand tools and general hardware
1600	Tobacco products	2899	Other fabricated metal products n.e.c.
1711	Textile fibre preparation; textile weaving	2911	Engines and turbines (not for transport equipment)
1721	Made-up textile articles, except apparel	2912	Pumps, compressors, taps and valves
1722	Carpets and rugs	2913	Bearings, gears, gearing and driving elements
1723	Cordage, rope, twine and netting	2914	Ovens, furnaces and furnace burners
1729	Other textiles n.e.c.	2915	Lifting and handling equipment
1730	Knitted and crocheted fabrics and articles	2919	Other general purpose machinery
1810	Wearing apparel, except fur apparel	2921	Agricultural and forestry machinery
1820	Dressing and dyeing of fur; processing of fur	2922	Machine tools
1911	Tanning and dressing of leather	2923	Machinery for metallurgy
1912	Luggage, handbags, etc.; saddlery and harness	2924	Machinery for mining and construction
1920	Footwear	2925	Food/beverage/tobacco processing machinery
2010	Sawmilling and planing of wood	2926	Machinery for textile, apparel and leather
2021	Veneer sheets, plywood, particle board, etc.	2927	Weapons and ammunition
2022	Builders' carpentry and joinery	2929	Other special purpose machinery
2023	Wooden containers	2930	Domestic appliances n.e.c.
2029	Other wood products; articles of cork/straw	3000	Office, accounting and computing machinery
2101	Pulp, paper and paperboard	3110	Electric motors, generators and transformers
2102	Corrugated paper and paperboard	3120	Electricity distribution and control apparatus
2109	Other articles of paper and paperboard	3130	Insulated wire and cable
2211	Publishing of books and other publications	3140	Accumulators, primary cells and batteries
2212	Publishing of newspapers, journals, etc.	3150	Lighting equipment and electric lamps
2213	Publishing of recorded media	3190	Other electrical equipment n.e.c.
2219	Other publishing	3210	Electronic valves, tubes, etc.
2221	Printing	3220	TV/radio transmitters; line comm. apparatus
2222	Service activities related to printing	3230	TV and radio receivers and associated goods
2310	Coke oven products	3311	Medical, surgical and orthopaedic equipment
2320	Refined petroleum products	3312	Measuring/testing/navigating appliances, etc.
2330	Processing of nuclear fuel	3313	Industrial process control equipment
2411	Basic chemicals, except fertilizers	3320	Optical instruments and photographic equipment
2412	Fertilizers and nitrogen compounds	3330	Watches and clocks
2413	Plastics in primary forms; synthetic rubber	3410	Motor vehicles
2421	Pesticides and other agro-chemical products	3420	Automobile bodies, trailers and semi-trailers
2422	Paints, varnishes, printing ink and mastics	3430	Parts/accessories for automobiles
2423	Pharmaceuticals, medicinal chemicals, etc.	3511	Building and repairing of ships
2424	Soap, cleaning and cosmetic preparations	3512	Building/repairing of pleasure/sport. boats
2429	Other chemical products n.e.c.	3520	Railway/tramway locomotives and rolling stock
2430	Man-made fibres	3530	Aircraft and spacecraft
2511	Rubber tyres and tubes	3591	Motorcycles
2519	Other rubber products	3592	Bicycles and invalid carriages
2520	Plastic products	3599	Other transport equipment n.e.c.
2610	Glass and glass products	3610	Furniture
2691	Pottery, china and earthenware	3691	Jewellery and related articles
2692	Refractory ceramic products	3692	Musical instruments
2693	Struct. non-refractory clay; ceramic products	3693	Sports goods
2694	Cement, lime and plaster	3694	Games and toys
2695	Articles of concrete, cement and plaster	3699	Other manufacturing n.e.c.

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2013.05.007.

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