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Macroeconomic exposure of developing economies to low-carbon transition

Guilherme Magacho[a,*], Etienne Espagne[b], Antoine Godin[a], Achilleas Mantes[a], Devrim Yilmaz[a]

[a] Agence Française de Développement, France
[b] World Bank, United States

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ABSTRACT

The low-carbon transition is a specific type of rapid structural change where low-emission industries grow and high-emission industries decline due to deliberate policies, changing preferences and technological change. Developing countries' macroeconomic exposure to this transition depends upon their reliance on carbon-intensive industries as a source of foreign currency, fiscal revenue, employment and wage income. Identifying these different dimensions of countries' exposure is important because different green policies need to be applied in different contexts, and the results of these policies will be more or less effective according to countries' idiosyncrasies.

This paper aims at providing estimates of countries' macroeconomic current exposures to the low-carbon transition. We develop a method to evaluate countries' external, fiscal and socioeconomic exposure, and, considering their capacity to adapt their productive structure, we analyse countries' vulnerabilities and risks in these different dimensions. Using a Hybrid World Input-output table for 189 countries, we identify the carbon-intensive industries, and then we estimate each country's direct and indirect dependence on these industries, considering countries' dependence for raising of foreign currency to analyse the external exposure, government revenue to evaluate the fiscal exposure, and the share of wages and employment to analyse the socioeconomic exposure.

Results show that countries present different degrees of exposure in different dimensions, and the degree of exposure varies significantly when indirect impacts are considered. Moreover, by analysing countries' capacity to adapt their production structure and resilience factors, we evaluate to what extent countries' macroeconomic exposure imply a higher vulnerability to the green transition process.

1. Introduction

The Paris Agreement was adopted in 2015 by 196 parties officialising a common aim to limit global warming to well below 2.0 (preferably 1.5) degrees Celsius compared to preindustrial levels (UNFCCC, 2015). To achieve this goal, carbon neutrality should be ensured in the second half of the century, implying that the remaining emissions after this period should all be compensated by existing carbon sinks. The Paris Agreement thus embarks all countries on a transformative effort of structural change for their economies. The increasingly ambitious Nationally Determined Contributions (NDC), together with the Long Term Strategies define this thin path between short-run development goals and longer run complete decarbonisation obligations (UNCTAD, 2021).

A fairly large group of economies are adopting deliberate policies and fostering technological change to promote the transition towards carbon neutrality. This new scenario is generating a rapid structural change, where low-emission industries (sunrise industries) are gaining importance and high-emission industries (sunset industries) are declining (Semieniuk et al., 2021). The consequences of this new dynamic of the global economy and how it propagates across countries depend on their industrial networks, on how these economies are connected to others through trade or finance, as well as on their tax structures and the composition of employment and income.

This paper aims at providing estimates of current macroeconomic exposure of countries to low-carbon transition. For this purpose, we develop a method to evaluate countries' external, fiscal and socio-economic exposure, and considering their sensitivity to

* Corresponding author at: 37bis Rue de la Grange aux Belles, 75010 – Paris, Île-de-France, France.

E-mail address: magachog@afd.fr (G. Magacho).

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the transition and their capacity to adapt their productive structure, we analyse their vulnerability and riskiness in these different dimensions. Using a Hybrid World Input-Output table for 189 countries, we define potential global sunset industries by taking into account their direct, upstream and downstream emissions, as indirect emissions often constitute a significant part of overall Greenhouse Gas (GHG) footprint (Downie and Stubbs, 2013). Once these sunset industries are defined, we estimate direct and indirect dependence of the economy on these industries in the aforementioned dimensions for all 189 economies in the EORA 26 database (Lenzen et al., 2012; 2013). Specifically, we calculate the share of net foreign exchange generated by sunset industries (via exports discounted by their import content), the share of government revenue generated by taxing sunset industries, and the share of wages and employment these sunset industries create.

Our paper thus contributes to the analysis of macroeconomic imbalances that emerge from rapid structural changes by providing estimates of multi-dimensional macroeconomic exposure to the low-carbon transition. Even though there are some recent studies discussing the systemic risks of the low-carbon transition, these studies mainly focus on the financial risks driven by stranded assets of large fossil fuel corporations (Caldecott, 2018), their capacity to engender financial instability and crisis (Monasterolo, 2020), and their cascading effects on other industries (Cahen-Fourot et al., 2021). The macroeconomic risks associated with low-carbon transition for an economy that heavily depends on these sunset industries, however, goes far beyond financial risks, since financial instability is only one of the possible systemic risks that may emerge during this transformative process (Mercure et al., 2021). Other important instabilities such as rising public debt, inflation, trade deficits and unemployment may emerge from the transition and may constrain economic growth, particularly for developing economies (Semieniuk et al., 2021).

Our results show that countries display varying degrees of exposure in different dimensions and these exposures also significantly change when indirect impacts are taken into account. Some countries, such as Algeria, Angola and Kuwait, suffer from high external exposure to green transition, whilst others such as Zimbabwe, Ethiopia and Paraguay display high fiscal and/or socio-economic exposure. Moreover, by employing alternative tools such as the Green Complexity Potential (Mealy and Teytelboym, 2020) to analyse the capacity of an economy to adapt its production structure to the transition and by analysing the prevalence/degree of social protection coverage, we also evaluate to what extent countries' macroeconomic exposure can constrain long-term growth and development and increase their vulnerability and systemic risks. Once again, our results indicate that high levels of exposure do not necessarily correspond to high degrees of vulnerability and risk.

The paper is organised as follows. Section 2 discusses the low-carbon transition from a structural perspective and along the three different dimensions of macroeconomic exposure defined in this paper: external, fiscal and socio-economic. Section 3 presents the methodology employed to estimate the indicators and data sources. Section four shows our main results at the country and sectoral levels. And finally, section 5 presents a multidimensional analysis of exposures, and applies cluster analysis to identify different groups of countries according to their specific types of exposure.

2. Literature review

The low-carbon transition can be seen as a unique type of rapid structural change, during which low-emission industries (sunrise industries) grow and high-emission industries (sunset industries) decline due to deliberate policies, changing preferences and technological advances (PRA, 2015; Semieniuk et al., 2021). Because countries have different structures of production, with different degrees of diversification and different policy tools at hand, this rapid transformation will have different social and economic impacts. The overall dynamics at the country level and its path-dependence during the decarbonisation phase will thus be strongly determined by its domestic industrial network, its dependence on sunset or sunrise industries and its connection with the rest of the world (mostly via the trade and financial balance), the public sector (via fiscal revenues) or households (via labour income and employment).

There is a close relation between product sophistication and emissions, where the greener products are usually those with higher technological content (Boleti et al., 2021; Romero and Gramkow, 2021). Developing economies are less diversified and less competitive in high-tech goods, as they do not have the productive and technological capabilities to produce them (Hidalgo, 2021). Therefore, on the demand side, less developed economies need to import capital goods and inputs to produce green energy and to reduce emissions. Moreover, on the production side, high-emission intensive industries may face a reduction in export revenues due to either reduction in the volume of sales or prices (Savona and Ciarli, 2019; Semieniuk et al., 2021). The capacity of countries to overcome the resulting balance-of-payment constraint depends on their capacity to adapt to changes in world demand and to produce domestically the goods and services necessary for this transition (Mealy and Teytelboym, 2020). Pegels and Altenburg (2020) recently showed that for developing and emerging economies, early greening is likely to bring economic co-benefits, in terms of efficiency-induced competitiveness and in gaining a foothold in the markets of the future. On the contrary, delaying this process risks permanent environmental damage, lock-in of polluting socio-technical pathways, and losses from asset stranding. Pegels and Altenburg (2020) still admit that careful timing and sequencing of green policy reforms are vital.

Public expenditures are necessary to promote green industries either via direct fiscal stimulus or by investments in green infrastructure, such as public mobility and renewable energy and other green technologies (IMF, 2020), as well as to mitigate the cost of the sunset industries. For many developing countries, sunset industries, such as fossil fuels, are a very important source of fiscal revenues, and hence the transition poses an imminent risk: governments need to increase spending while the low-carbon transition itself may reduce fiscal revenues (IEA, 2019). The transition can thus be costly for governments, and difficult to be implemented in highly indebted countries, with strong path dependence in the longer run. Furthermore, although the net impact of low-carbon transition on employment is expected to be positive in the long run, the costs of retraining re-allocated workers and of social spending to guarantee basic needs for unemployed workers will be large (Saget et al., 2020). However, the drop in fiscal revenues due to a rapid structural change, may lead to a higher exposure of countries that are excessively dependent on these industries as a source of fiscal revenue (Semieniuk et al., 2021).

A country's productive structure and capacity to adapt determines not only their economic growth trajectory but also has important distributional effects. Hartmann et al. (2017) show that countries with higher capacity to adapt and with higher product diversification tend to have more capacity to generate and distribute income. Rosemberg (2010) discusses the impact on job creation and destruction in regions that depend on carbon-intensive industries, arguing that a "just transition" needs to account for the associated decline in living standards. According to Saget et al. (2020), although the net impact of transition on employment is expected to be positive, there will be large imbalances, with countries more dependent on these industries to generate employment tend to be more impacted than others.

Imbalances will also depend on the nature of green jobs and the way job transitions are strategically managed. Although Consoli et al. (2016) find that US green jobs use high-level abstract skills significantly more than non-green jobs. Furthermore, according to Bowen et al. (2018), only very few of those green jobs consist of green tasks. This suggests that the term "green" should be considered as a continuum rather than a binary characteristic. In the end, most retraining can happen on-the-job, at least as far as US job data are concerned. Chen et al. (2020) consider the specific case of the post-pandemic recovery and the roles of skills for a resilient recovery. More specifically, they address the potential for job training programs to help ease the transition to a green economy.

Different climate policies, such as carbon pricing, subsidies for green investments and direct investments in green infrastructure will have very different social and macroeconomic impacts in different contexts. Carbon pricing has the advantage of having no direct fiscal costs, but it may lower real GDP by immediately increasing the cost of energy (IMF, 2020). Moreover, Moz-Christofoletti and Pereda (2021) and Dorband et al. (2019) show that the distributional impacts of carbon price tends to be negative. Despite being effective in reducing emissions in the short run, carbon price imposes welfare losses, especially on the poor. Green fiscal stimulus, on the other hand, despite having high fiscal costs, boosts economic growth both directly and indirectly by increasing aggregate demand and promoting productivity growth in low-carbon sectors (IMF, 2020). However, as developed in Chen et al. (2020), the effectiveness of green stimulus spending varies depending on the prevalence of jobs using green skills in a community prior to the stimulus.

According to Peszko et al. (2020), some advanced economies, such as the EU countries that are less dependent on sunset industries, may experience low economic costs during the transition, as renewables are already part of the energy mix and imports already embed the intensive use of fossil fuels. On the other hand, countries relying heavily on current and future export revenues from sunset industries are likely to face the largest challenges. The authors present evidence that for some groups of countries, the low-carbon transition will have positive impacts, whilst for others, the negative impacts on the economy may not be compensated for by the positive impacts of the structural transformation. Therefore, all things equal on the international side, a country-level low-carbon transition needs to navigate between a variety of idiosyncratic macroeconomic vulnerabilities and risks, which strongly determine the set of feasible pathways.

A complete macroeconomic assessment of the long-run consequences of a low-carbon transition at the country level would typically require dynamic modelling of sectoral trends and their full integration into a macroeconomic framework that is outside the scope of this paper. This type of modelling is rather expensive in terms of data, adaptation of the modelling framework to the institutional context and hence it would be illusory to try to develop a comprehensive assessment for all countries in the world and with granular sectoral aspects. The methodology we propose here allows for such comprehensive exercise, albeit in a static framework. The results thus present a multi-dimensional perspective on the current exposure to sunset industries in the context of a low-carbon transition. As such it provides useful information to indicate which sectors in which countries have to be monitored and the nature (external, fiscal, socio-economic, or all) of countries' vulnerabilities.

3. Methods and data

The Input-output (IO) framework, initially developed by Leontief (1936, 1941), is an important tool to analyse the interdependence of industries either within an economy or across different economies. Basic IO models are built from observed data from a specific region (usually a country), providing information about the intersectoral productive relations (Miller and Blair, 2009). Multiregional IO models (MRIO) were further developed to account also for the interrelation between industries in different regions (Chenery, 1953; Moses, 1955), which is especially interesting in globally integrated production systems.

Even though Leontief (1936) conceived IO matrices as industry production functions, where physical quantities of inputs were necessary to produce goods, most IO matrices were built upon monetary data due to data collection requirements. Nevertheless, hybrid IO matrices, sometimes referred as energy or environmental IO matrices, initially put forward by Cumberland (1966), and systematized by Bullard and Herendeen (1975), allow us to identify some physical flows embodied in intermediate inputs, and hence it is an important framework to analyse the low-carbon transition. Essentially, hybrid MRIO allow us to understand the direct and indirect environmental impacts of production and demand within and across countries (Guilhoto, 2021).

All of the methodologies described in the following sections are based on adaptation of the Leontief (1936) or Ghosh (1958) models. Both models are widely used in the economic literature to identify sectorial dependencies, either from a demand shock (Leontief model) or from a supply shock (Ghosh model). Limitations of both models relate to constant return to scale assumptions, to the perfect elasticity of inputs or demand and to the perfect substitutability among input factors (Oosterhaven, 1988; Dietzenbacher, 1997; Galbusera and Giannopoulos, 2018). These models can nonetheless be usefully employed to compare and contrast economic structures, sectorial relative economic/environmental importance (see for instance Zhang, 2010; Antràs et al., 2012; Aldasoro and Angeloni, 2015; Piñero et al., 2019; Zhang et al., 2020; Cahen-Fourot et al., 2020) and to assess indirect effects of climate policies (see for instance Chen et al., 2020; Hebbink et al., 2018; Bastidas and McIsaac, 2019; Perrier and Quirion, 2018). They are however static models and as such the results presented here should be analysed as current exposure. Any long-term analysis would require dynamic modelling which, as we stressed above, is beyond the scope of this paper.

The main data source for analysing countries' exposure is the EORA-26 Hybrid-MRIO (Lenzen et al., 2012; 2013). This database provides information for monetary input–output coefficients for 189 countries and 26 industries, as well as physical data on material use, waste and emissions. The level of sectoral disaggregation, however, is a relevant issue for our analysis. As sunset industries cannot be defined at the 26-industry level, exposure analysis is complemented by EXIOBASE 3xr, which updates EXIOBASE (Peters, 2008). EXIOBASE 3xr standardized production for 200 products and 164 countries, which allows us to identify which sunset industries are effectively within the potential sunset industries. Based on this complementary dataset, we can focus, for example, only on electricity from fossil fuels (rather than aggregate electricity production), as well as exclude from metals products and mining industries those metals and ores that are important for the transition, such as copper and lithium (IEA, 2021).

3.1. Sunset industries and emission-intensity

Before analysing countries' macroeconomic exposure, vulnerabilities and risks to the low-carbon transition, we need first to identify the potential sunset industries. Industries with substantial contributions to decarbonisation are expected to grow and gain momentum, whilst industries that have significant environmental footprint are expected to lose importance. Despite its limitations, a first approach to the definition of these industries can be based on their GHG emission-intensity, as discussed by the European Union Technical Export Group (EU-TEG, 2020). Hence, we first compute the emission content of each industry for each country. Besides the direct emission during the production process, we estimate indirect emissions both upstream (emissions embodied in intermediate inputs) and downstream (emissions after production until final consumption) using the hybrid MRIO.

Emission intensity can be defined as CO2 emissions by unit of production or as CO2 equivalent, which includes other Greenhouse Gases (GHG) emissions, per unit of production. Once all monetary relations in MRIO tables are in the same currency (USD), the unit of production adopted here is US dollars. Therefore, emission intensity is defined as the relation of CO2 or CO2 equivalent (CO2e) emissions per dollar. The EORA-26 database compiles direct emissions by industry and country from different sources. The emissions calculated by the Emissions Database for Global Atmospheric Research (EDGAR) was compiled in the EORA-26 structure, and hence CO2 emissions data for all the 189 countries are available.[1] By dividing CO2 emissions by total production by industry for a given country, we get the direct emission intensity (e^d) of an industry in a country (i), as follows:

$$e_i^d = \frac{Emission_i}{x_i} \quad (1)$$

where x_i is the production of an industry in a country, and $Emissions_i$ is this industry emissions.

In order to obtain upstream indirect emissions, we need to consider not only emissions embodied in direct inputs, but also emissions embodied in all inputs necessary to produce these direct inputs. Following Miller and Blair (2009), one can obtain the Multiregional Leontief matrix by considering that total production by industry and country is given by the summation of the column-vector of intermediate inputs and the column-vector of final demand ($\mathbf{f}$), and intermediate inputs are given by the multiplication of the technical coefficient matrix ($\mathbf{A}$) and the column-vector of total production ($\mathbf{x}$):

$$\boldsymbol{x} = \boldsymbol{Ax} + \boldsymbol{f} \quad (2)$$

Alternatively, one can write it as

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f} \quad (3)$$

where $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief matrix, which shows the direct and indirect inputs needed to produce one unit in each industry.

The backward indirect emissions can be obtained by pre-multiplying the diagonalized vector of direct emission coefficient by industry ($\hat{\mathbf{e}}$) by the Leontief matrix, and subtracting the direct emissions:

$$\boldsymbol{e^i} = \mathrm{e}\boldsymbol{L} - \mathrm{e} \quad (4)$$

The result is a matrix where columns are the industries under consideration (for each country) and lines are the industries responsible for emitting directly. The summation of the elements of each column gives a vector of backward indirect emissions by industry and country.

In order to identify the downstream (or forward) emissions, i.e. those arising from the use of the goods and services produced by the industries under consideration, it is necessary to use the Ghosh (1958) supply-side, model, rather than the Leontief one mentioned above. Different from the Leontief model, which accounts for the use of inputs by one industry, the Ghosh model allows us to identify by which industries an input is being used from the moment it is produced until its final use. Accounting for downstream emissions is therefore identifying the total emissions indirectly associated with this input after its production.

Following the notation by Miller and Blair (2009), we have that

$$\boldsymbol{G} = (\boldsymbol{I} - \boldsymbol{B})^{-1} \quad (5)$$

where **G** is the Ghosh matrix and **B** is the direct-output coefficients.

Based on this, we can calculate:

$$\boldsymbol{e^{if}} = \boldsymbol{G}\mathrm{e} - \mathrm{e} \quad (6)$$

and by summing up the elements of each line of $\mathbf{e^{if}}$, we obtain the forward (indirect downstream) emission intensity.

Based on these results, we can analyse which industries are the potential sunset industries, i.e.: those industries with the higher direct and indirect emission intensity. It is important to note, however, that they are only potential sunset industries. First, despite high-emission intensity, industries which will replace industries with even higher emission-intensity will not shrink due to the low-carbon transition. Instead, they will be important for reducing global emissions, and rather than a reduction in their shares in the world economy, it is expected that these industries will grow relatively more. Nevertheless, investments in reducing the emissions within these industries are necessary either to change the inputs used for production or to change their process of production. Second, there is a high geographical disparity of emissions within a single sector such that some carbon emitting industries in specific countries might benefit from the transition because they will replace identical industries in other countries. This might be the case, for example, when the EU Carbon Border Adjustment Mechanism starts being implemented (Magacho et al., 2022). Therefore, in order to define the actual sunset industries, there is a need to first identify which are the high emission intensive industries globally, and then exclude those industries that either are not high emission intensive within the country or are important to replace other industries despite presenting high emission intensity.[2]

Once sunset industries are defined in this way, we can analyse countries' dependence on these industries to evaluate their macroeconomic exposure to the low-carbon transition.

3.2. External exposure

In order to account for countries' external exposure to the low-carbon transition, we estimate countries' dependence on sunset industries by calculating the sectoral net foreign exchange generation. This measure shows the volume of foreign exchange that would have been lost if the country stops exporting products of sunset industries, considering that some foreign exchange is needed to produce these goods as they embody imported inputs.[3]

Sectoral exports per unit of production (exp) is given by:

$$exp_i = \frac{Exports_i}{x_i} \quad (7)$$

where $Exports_i$ is total exports of a country by sector.

However, as we stressed above, to produce these exported goods, countries need to import inputs. Therefore, to measure the

[1] The EORA-26 also compiles direct GHG emissions from the PRIMAP-Hist national historical emissions time series. However, this data is available only for developed countries and the largest developing economies, which may lead to relevant bias in the analysis.

[2] Despite this consideration, in this article, declining industries are defined at the global level rather than at the country level. As presented by Magacho et al. (2022), in these industries there is a high dispersion of carbon intensity, but the vast majority of countries have high emissions in all industries considered to be effective sunset industries.

[3] It is important to note that we account only for foreign exchange raised by trade, ignoring capital flows. Despite their importance for many countries, we seek to identify here the importance of these productive sectors to raise foreign exchange and analyse their dependence. As discussed in the last section, further works could complement this analysis by considering capital flows, such as sectoral Foreign Direct Investments (FDI).

net generation of foreign exchange by each sector, it is necessary to calculate the direct and indirect embodied imported inputs. In the MRIO framework this can be obtained as:

$$\boldsymbol{m} = \imath^{\boldsymbol{T}}[\boldsymbol{A}^{\boldsymbol{M}}(1 - \boldsymbol{A})^{-1}] \quad (8)$$

where

$$\boldsymbol{A}^{\boldsymbol{M}} = \boldsymbol{A} \odot (1 - \boldsymbol{D}) \quad (9)$$

m is the row-vector of direct and indirect embodied imported inputs, $\imath$ is a column-vector of ones, **D** is a dummy matrix of ones in the within countries' sectoral relations and zeros in the trade flows (imports and exports) and $\odot$ denotes the element-wise multiplication.

Net generation of foreign exchange by unit of production (nx), discounted by the direct and indirect embodied imported inputs, is thus given by:

$$nx_i = exp_i(1 - -m_i) \quad (10)$$

where m_i is the imported content of production of a country by sector.

Finally, to measure the importance of the sunset industries in total net raise of foreign exchange,[3] we sum up the net raise of foreign exchange of these industries by country and divide by the total raise of foreign exchange:

$$NX^S = \frac{\sum_{i \in S} nx_i x_i}{\sum_i nx_i x_i} \quad (11)$$

where s is the set of all the sunset industries for the country under consideration.

3.3. Fiscal exposure

In order to identify which countries are most exposed to the low-carbon transition in the fiscal dimension, we estimate the countries' fiscal revenue dependence on sunset industries. Besides considering the share of these industries in total fiscal revenues, we also take into account that some non-sunset industries might be negatively affected by the transition. We thus consider the upstream industries that supply inputs for sunset industries (directly and indirectly), as presented in Fig. 1. The total fiscal contribution of sunset industries is then calculated as the sum of tax revenues raised from sunset industries and those from the industries that supply inputs for sunset industries.

Before estimating the direct and indirect fiscal exposure, following the Hypothetical Extraction Technique (HET) (Dietzenbacher and Lahr, 2013), we need to calculate the sectoral output that is not related to sunset industries neither directly nor indirectly. Once sectoral output is defined as

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f} \quad (12)$$

we can define vector of sectoral output not related to sunset industries ($\mathbf{x^n}$) as

$$\boldsymbol{x^n} = (\boldsymbol{I} - \boldsymbol{A^n})^{-1}\boldsymbol{f^n} \quad (13)$$

where $\mathbf{A^n} = \mathbf{d^n} \odot \mathbf{A}$, $\mathbf{f^n} = \mathbf{d^n} \odot \mathbf{f}$ and $\mathbf{d^n}$ is a column-vector of ones for sectors that not include sunset industries, and with the share of effective non-sunset industries for sectors that might include sunset industries. Essentially, the HET applied here assumes that both final demand and production for other industries are hypothetically inexistent in sunset industries, and by recalculating the Leontief system without them, one can measure their direct and indirect importance for the economy.

Once we have the sectoral output that is not related to sunset industries and the total output per sector, we can calculate countries' fiscal exposure to the low-carbon transition as the share of fiscal revenues that is related to sunset industries directly or indirectly:

$$FR^S = 1 - \frac{\sum_i x_i^n t_i}{\sum_i x_i t_i} \quad (14)$$

where t_i is sector i direct taxation of the country under consideration.

Taxation on products by unit of production (t_i^P) can be obtained directly from the EORA-26 database by dividing the total taxation on products by the total output

$$t_i^P = \frac{Taxes_i}{x_i} \quad (15)$$

where $Taxes_i$ is the effective tax on products, which includes value-added taxes and other taxes levied on the production and sale.

Besides production taxes, some sectors may contribute more to countries' total revenue than others if profits and wages are taxed at different rates. For most of the countries under consideration, however, we do not have the sectoral taxes levied on profits and wages. Therefore, we consider that tax on profits is uniform across sectors within a country as well as tax on wages, which includes social contributions. Based on the Government Finance Statistics (GFS/IMF), we estimate the sectoral tax contributions on profits and wages as:

$$t_i^Y = \frac{ProfTaxes}{Profits}\frac{Profits_i}{x_i} + \frac{WageTaxes}{Wages}\frac{Wages_i}{x_i} \quad (16)$$

where $ProfTaxes$ and $WageTaxes$ are taxes on profits and wages, respectively (both from the GFS/IMF database), and $Profits$ and $Wages$ are total profits and total wages, respectively. Profit taxes includes Taxes on income, profits, and capital gains payable by corporations and other enterprises, whilst Wage taxes includes Taxes on income, profits, and capital gains payable by individuals, Taxes on payroll & workforce and Social contributions.

The summation of taxes on products and on income per monetary unit of production then gives the sectoral direct contribution to fiscal revenues:

$$ti = tPi + tiY \quad (17)$$

3.4. Socio-economic exposure

EORA-26 has data on wages, allowing us to calculate direct and indirect wage contributions of sunset industries directly. Direct sectoral wage contribution by unit of production is given by

$$w_{i,j} = \frac{Wages_{i,j}}{x_i, j} \quad (18)$$

Based on this, we can calculate the direct and indirect share of wages in sunset industries (W^S) as

$$W^S = 1 - \frac{\sum_i w_{i,j} x_{i,j}^n}{w_{i,j} x_{i,j}} \quad (19)$$

EORA-26 does not contain employment data but ILOSTAT provides employment data for 177 of the 189 countries available in EORA-26. The sectoral aggregation is however different between the two data-sources, thus requiring conversion manipulation. We assume that sectoral employment per unit of production in ILOSTAT sectors is the same for all corresponding sectors in EORA-26 for a given country, as presented in Table 1.

Therefore, direct employment per output (n) in sector i for country j is given by:

$$n_{i,j} = \frac{Empl_{k,j}}{x_{k,j}} \quad (20)$$

where k is the sector according to ILOSTAT database.

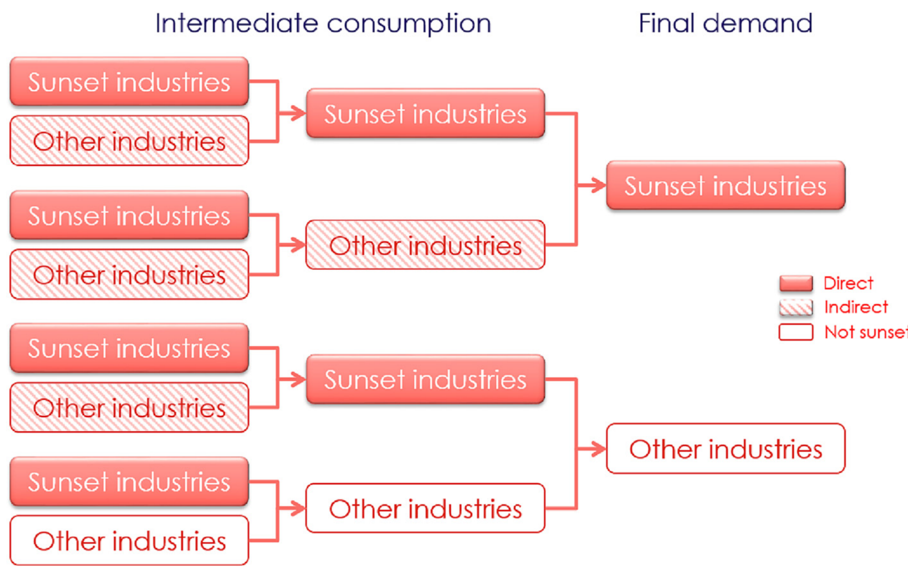

Fig. 1. Direct and indirect sunset related industries.

Once we have direct sectoral employment per output, we can calculate the direct and indirect share of employment in sunset industries (N^s):

$$N_j^S = 1 - \frac{\sum_i n_{i,j} x_{i,j}^n}{\sum_i n_{i,j} x_{i,j}} \tag{21}$$

4. Countries' exposure and vulnerabilities

In order to determine each country's exposure, we first define potential sunset industries. We then combine direct and indirect dependencies, along the three dimensions already defined, of each country with its capacity to migrate to other industries or its capacity to absorb losses to evaluate that country's exposure to a low carbon transition.

4.1. Defining sunset industries

Total CO2 emission-intensity is considered here as the key variable to determine which industries can be considered as sunset industries. However, as mentioned above, some industries may display high emission-intensity, but they should not be considered a sunset industry because they will replace industries with higher environmental impacts. This is the case with Recycling, which is among the most CO2 emission-intensive industries, but is excluded from the list of potential sunset industries, as it is an industry capable of substituting many other industries with much higher environmental impacts.

Figs. 2 and 3 presents a box-plot for CO2 emission-intensity for the sectors of the EORA-26 database. From Fig. 2, which accounts for direct and upstream indirect emissions, we can see that, besides Electricity, gas and water, which is the sector with the highest emission-intensity, three other sectors also present high levels: Petroleum, chemical and non-metallic mineral products; Metal products and Recycling. Moreover, Electrical and machinery, other manufacturing, Textiles and Wearing apparel and Transport equipment, as well as Mining and quarrying, also present high CO2 emission-intensity, but not as high as the sectors discussed before.

From Fig. 3, which accounts for downstream emissions, we can see that Mining and Quarrying is the sector with the highest GHG emission-intensity. Petroleum, chemical and non-mineral metals, Electricity, gas and water, and Metal products also present high levels of CO2 emissions per unit of production, even though not as high as Mining and quarrying.

Table 2 organises these sectors according to their emission intensity levels. There are no industries with high emission-intensity considering both upstream and downstream emissions.

Table 1
Sectoral correspondence.

Sector in ILOSTAT	Sector in EORA
Agriculture, forestry and fishing	Agriculture Fishing
Mining and quarrying	Mining and Quarrying
Manufacturing	Food & Beverages Textiles and Wearing Apparel Wood and Paper Petroleum, Chemical and Non-Metallic Mineral Products Metal Products Electrical and Machinery Transport Equipment Other Manufacturing Recycling
Utilities	Electricity, Gas and Water
Construction	Construction
Wholesale and retail; trade repair of motor vehicles and motorcycles	Maintenance and Repair
	Wholesale Trade Retail Trade
Transport; storage and communication	Transport Post and Telecommunications
Accommodation and food service activities	Hotels and Restaurants
Financial and insurance activities	Financial Intermediation and Business Activities
Real estate; business and administrative activities	
Public administration and defence; compulsory social security	Public Administration
Education	Education, Health and Other Services
Human health and social work activities	
Other services	Private Households Others
Re-export & Re-import	Re-export & Re-import

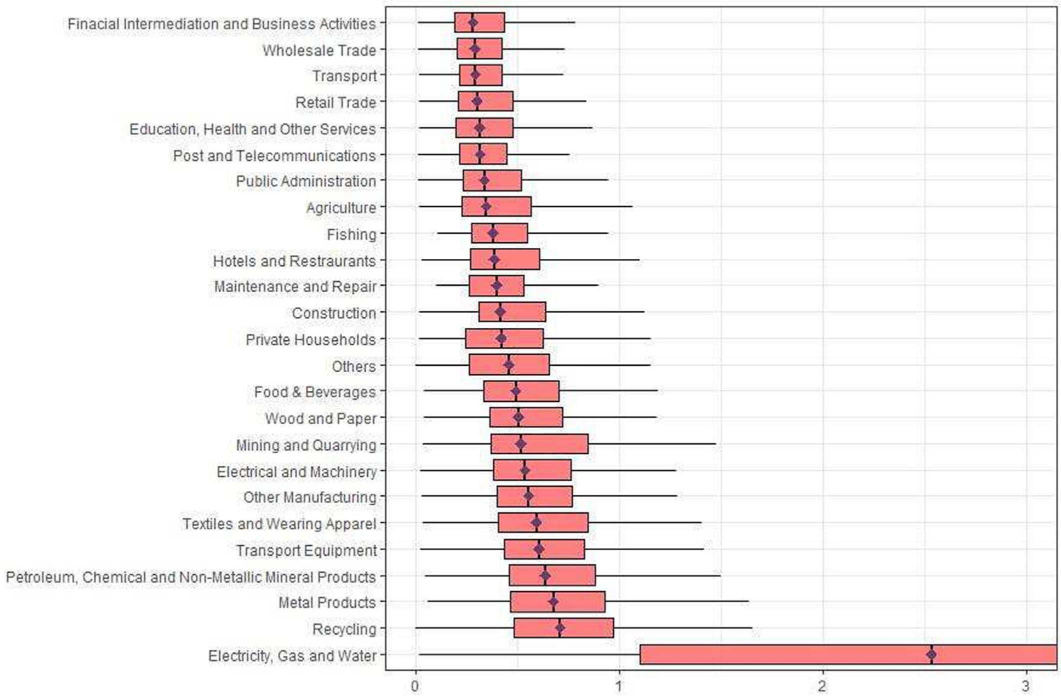

Fig. 2. Direct and upstream indirect CO2 emission-intensity (Kg of CO2 per USD). The box-plot above present the dispersion of data across countries in the x-axis. The end-points of the lines are the maximum and minimum, the end-points of rectangles are the first and thirds quartiles, and the blue diamond is the median. Authors' calculation based on EORA-26 data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

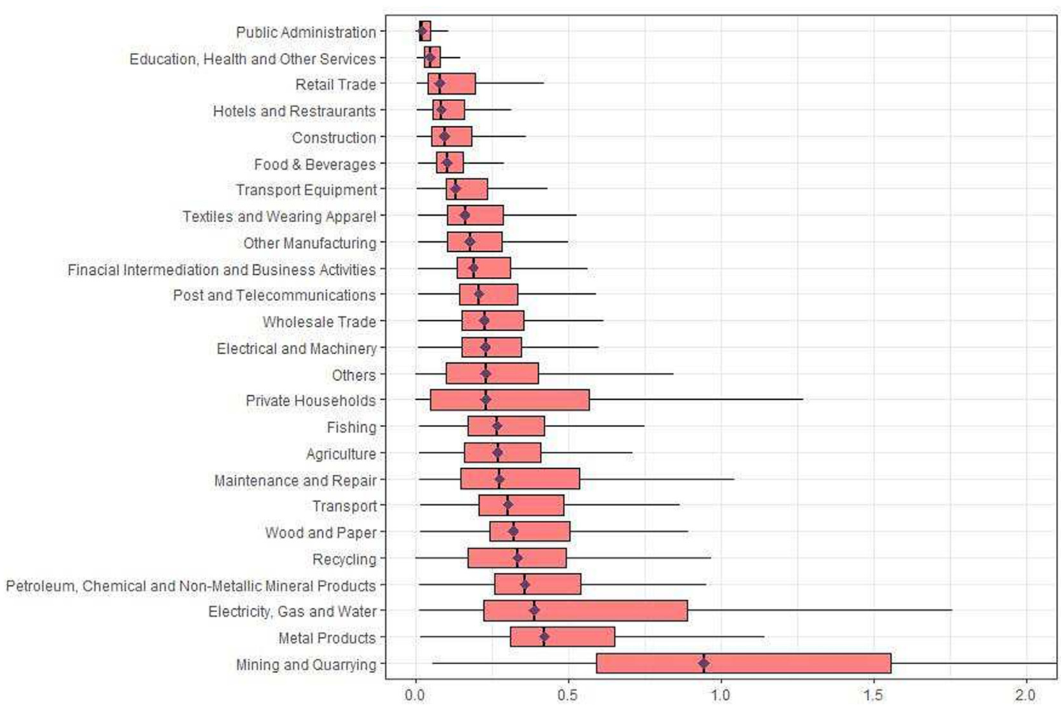

Fig. 3. Downstream indirect CO2 emission-intensity (Kg of CO2 per USD) The box-plot above present the dispersion of data across countries in the x-axis. The end-points of the lines are the maximum and minimum, the end-points of rectangles are the first and thirds quartiles, and the blue diamond is the median. Authors' calculation based on EORA-26 data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

However, Mining and quarrying presents a very high downstream emission-intensity. This is mainly because many products produced in this sector are used as an input in activities that present high emission-intensity, such as electricity from fossil fuels and steel production. Therefore, despite not being a high-emitting industry, it should be seen as a potential sunset industry, once one can expect that low-carbon transition policies will impact some industries within this sector.

Metal products, Recycling, Petroleum, chemical and non-metallic mineral products and Electricity, gas and water present

Table 2
Upstream and downstream GHG emission-intensity.

	Low upstream	Medium upstream	High upstream
Low downstream	All other sectors	Electrical and mach. Other manufacturing Textiles Transport equipment	Recycling
Medium downstream			Chemicals* Metal Products Electricity**
High downstream		Mining and Quarrying	

(*) Petroleum, chemicals and non-metal minerals; (**) Electricity, Gas and Water.

high upstream emission-intensity, and except from Recycling, medium downstream emission-intensity. As discussed before, Recycling is a special industry for the transition as it provides inputs that may replace highly emitting industries. The other three industries, however, together with Mining and quarrying, are the most important sectors in terms of emission per unit of production, and hence they are considered as potential sunset industries as they are expected to be the most negatively impacted by the low-carbon transition.

The fact that an industry in a particular country is defined as a sunset industry does not imply that it is indeed a sunset industry for all countries. In fact, the intra sectoral composition of trade and production varies substantially across countries, and one must account for these differences. In the electricity sector, for example, many countries present a low dependence on fossil fuels, and for these countries, this sector cannot be considered as a sunset industry. To account for these differences, based on the EXIOBASE 3rx (Peters, 2008) we calculate the share of output and trade within potential industries by country that can be considered as a sunset industry.[4] The following industries were considered as effective sunset industries: Electricity from fossil fuels; Cement, lime and plaster; Basic iron and steel and ores; Aluminium products and ores; Nitrogen fertilisers; and Fossil fuels extraction and its deviates (coal, petroleum and gas). The share of effective sunset industry exports within the potential sunset industries was applied to calculated raise foreign exchange, and the share of output was applied to obtain the other variables.[5]

4.2. External and fiscal exposure

Now that potential sunset industries are defined as above, we move on to calculate the external, fiscal and socio-economic exposure of each country, considering its dependency on these industries to generate foreign exchange, raise fiscal revenues, create employment and pay wages.

Before we present the results, we must note that high exposure does not mean that the economy will be necessarily impacted by the low-carbon transition, as we briefly mentioned in the introduction. Countries with high productive and technological capabilities can more easily migrate from one product to another, implying that despite being exposed to the low-carbon transition, countries with high technological sophistication are less vulnerable. Mealy and Teytelboym (2020) developed a method to estimate countries' capabilities in green products (as defined in different taxonomies), based on the Economic Complexity Approach (Hidalgo, 2021). The Green Complexity Potential (GCP) indicates which countries have higher technological and productive capabilities to migrate to green products based on the products for which they already are competitive.

Fig. 4 presents countries' external exposure in the vertical axis, measured by the share of net foreign exchange revenues from sunset industries, and the fiscal exposure in the horizontal axis, measured by this dependence in terms of fiscal revenue. The GCP rank is represented by the colour of the points.

The most vulnerable countries to the low-carbon transition in external terms are the red points in the top of the graph, whilst the most vulnerable in fiscal terms are the red points in the right hand side. These countries combine a higher exposure and low technological and productive capabilities to migrate to green products. The dashed line is on the third quartile, indicating that countries in the top right part are those with very high external and fiscal dependence on potential sunset industries.

On the top of Fig. 4, we have the countries with the higher external vulnerability. Algeria (DZA), Angola (AGO), Venezuela (VEN), Iraq (IRQ), Libya (LYB), Bahrein (BRN), Congo (COG) and Yemen (YEM) are extremely exposed to the low-carbon transition in this context, as more than 60% of their net foreign exchange revenues from trade come from sunset industries, and they rank among the countries with less GCP, indicating that they have low capabilities to migrate to green products. These economies depend on sunset industries to avoid large current account deficits and hence balance-of-payments crises.

On the other hand, countries such as Russia (RUS), Iran (IRN) and Norway (NOR), despite presenting high exposure to the low-carbon transition (more than 50% of the foreign exchange revenues from trade come from sunset industries), are relatively more capable of moving to green industries, which means that they are less vulnerable economies. Nigeria (NIG), Saudi Arabia (SAU), Oman (OMN) and Bolivia (BOL) also present a high level of exposure, but they have less technological and productive capabilities to produce green products, which indicates that they are more vulnerable than Russia, Iran and Norway, even though they present similar levels of exposure.

Some economies, such as Ukraine (UKR), Croatia (HRV) and Indonesia (IDN), present a degree of exposure higher than the average (about 20% of the revenue of foreign exchange is from sunset industries), but they rank among the countries with the higher potential to migrate to green products, according to the GCP index. Therefore, even though these economies are exposed to the low-carbon transition in terms of the external dimension, they display low vulnerability, as they can more easily migrate to green products, and replace sunset industries with green industries.

Countries in red located in the right side of Fig. 4 are those with the highest fiscal vulnerability, as they depend directly or indirectly on sunset industries to raise government revenue. This is the case of Kuwait (KWT), Trinidad and Tobago (TTO), Algeria (DZA), Bolivia (BOL) and Venezuela (VEN). Moreover, because none of these economies displays a high GCP, they are less capable of migrating their productive structure to green industries, implying that the low-carbon transition may impose relevant fiscal risks for these countries.

The case of India (IND), South Korea (KOR) and Belarus (BLR), however, is significantly different. First, despite being among the most exposed countries from a fiscal point of view, they are not very exposed from an external perspective. Most important, how-

[4] We considered as effective sunset industries the following industries in EXIOBASE 3rx. These industries were chosen because they contribute the most for CO2 emissions and they have been the target of policy actions, such as the EU Carbon Border Adjustment Mechanism (Magacho et al., 2022).

[5] The underlying assumption behind this is that the technical coefficient of a country for effective and potential sunset industries are the same. This assumption might create some distortions in the results, but due to the lack of data, it is not possible to have these coefficients at the product level, especially for developing countries, which are the focus of this study. With more granulated MRIO tables for developing countries, it will be possible to achieve better estimates.

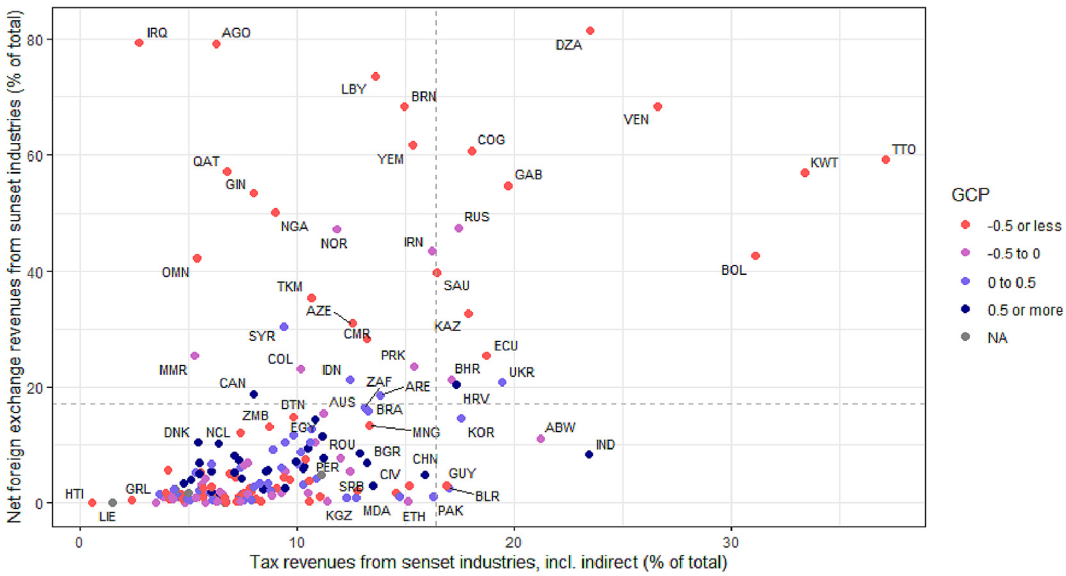

Fig. 4. Countries' external and fiscal exposure to the low-carbon transitionSee Appendix B for country codes and names.

ever, is the fact that these economies are among those with the highest green complexity potential, which means that, despite depending on declining industries as a source of tax revenue, they have the productive and technological capacities to migrate their productive structure for green industries.

Fig. 5 decomposes the net foreign exchange revenues from trade and fiscal revenues by potential sunset industries and present these data for the one-fifth most exposed countries.

The vast majority of the economies with the highest external exposure (figure on the left) are dependent on Mining and quarrying to raise foreign exchange. Among the first quintile group of countries that depend the most on sunset industries to raise foreign exchange, only Russia (RUS), Kazakhstan (KAZ), Bahrain (BHR), Ukraine (UKR), Croatia (HRV), South Africa (ZAF) and Brazil (BRA) do not depend exclusively on this sector. In the case of Ukraine, Kazakhstan and Bahrain, industries within Metal products, such as iron and steel, are the most important source of foreign exchange among sunset industries. In the case of Russia, Bahrain, Croatia, South Africa and Brazil, the sector "Petroleum, chemicals and non-mineral metals" is also important for guaranteeing external sustainability. These countries may be seen, therefore, as less vulnerable compared to the other most exposed countries if one considers that their sources of foreign exchange are more diversified and come from processing activities (not only from extraction). Despite also depending on sunset industries, this diversification reduces the dependence on a specific sunset indus-

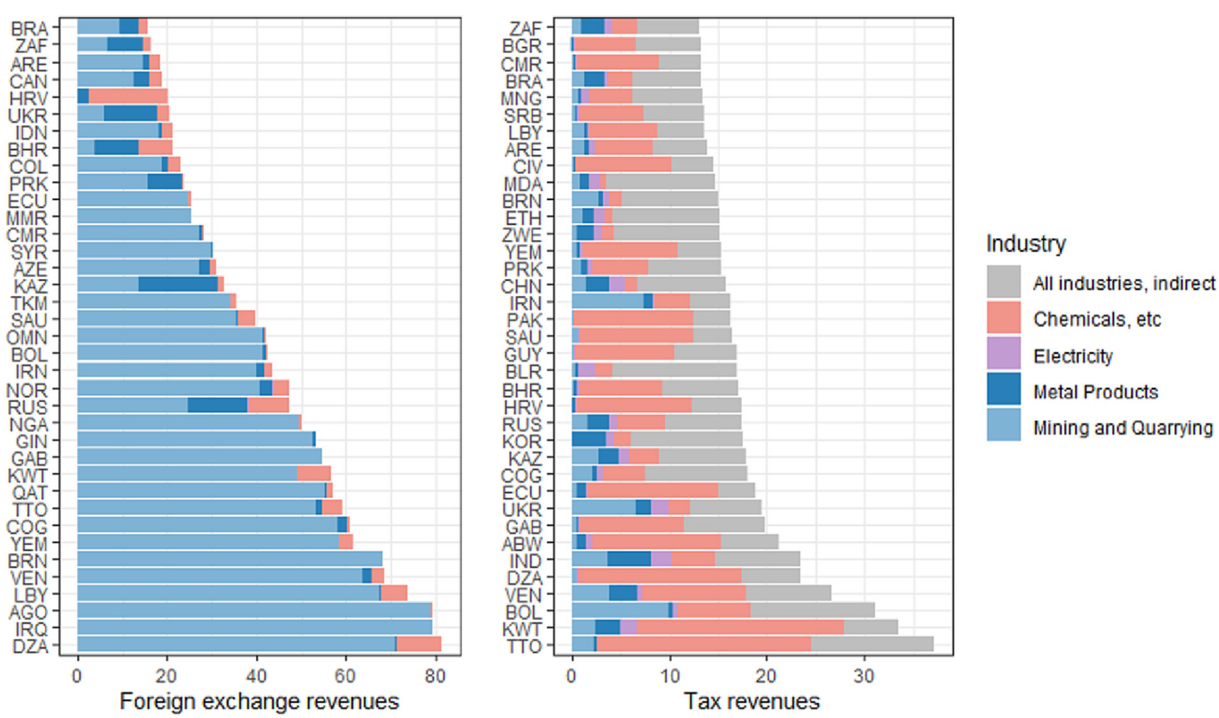

Fig. 5. Foreign exchange and tax revenues by sector, most exposed countries See Appendix B for country codes and names.

try, and hence policy measures that impact one target industry will have lower impacts in these countries.

Another important issue that emerges from these results is the discrepancy among countries in terms of their dependence on sunset industries, even among the most exposed ones. While for Algeria (DZA), Angola (AGO) and Iraq (IRQ), these industries contribute around 80% for the foreign exchange revenues from trade, in Ukraine (UKR), Indonesia (IDN), and Bahrain (BHR), this share is around 20%. Because in the most exposed countries the export basket is concentrated in few non-processed products, policy measures around the globe towards low-carbon transition might significantly reduce their foreign revenues, and if they are not capable of changing their structure of exports towards less emitting industries, the negative impact of transition will be relatively larger.

The right side of Fig. 5 shows the sectoral contribution for the aggregate fiscal exposure level. In contrast to the sectoral contribution for external exposure, fiscal exposure also accounts for indirect impacts, which take into account the (non-sunset) industries that supply for sunset industries. As we can see from this figure, the sectors that contribute to fiscal exposure are different from those that contribute to external exposure. Whilst in the external exposure Mining and quarrying is the most relevant industry for the vast majority of countries, the list is much more heterogeneous for fiscal exposure, with Petroleum, chemical and non-mineral metals arising as the most important sector. The lower importance of Mining and quarrying is expected as it is usually a sector that is relevant for exports but not as relevant for countries' total production.

This is an interesting result from an analytical point of view because it shows that Mining and quarrying is not the sector that provides most of the fiscal revenue among sunset industries, except for Bolivia (BOL), Ukraine (UKR), Iran (IRN) and Indonesia (IDN). The Petroleum, chemical and non-mineral metals sector includes refined fossil fuels, fertilizers and cement, which are sectors that employ many people with high wages (as we will see below), and once we consider not only taxation on products but also direct taxation on income, we can see their importance in terms of fiscal revenue for the countries.

It is also interesting to note that for some countries, such as Congo (COG), Kazakhstan (KAZ), South Korea (KOR), Belarus (BLR) and China (CHN), indirect impacts contribute the most. Since these impacts capture not only the production for domestic industries but also the production for other countries' industries, this result may indicate that non-sunset industries of these economies are vulnerable because they depend on the demand of other economies' potential sunset industries. Therefore, although these countries seem to be less exposed when only total production is accounted for, by using the multi-regional input–output (MRIO) framework we can verify that they may in fact display higher levels of exposure. MRIO tables allow us to account for inter-country impacts more systematically, and provides a much broader perspective on the exposure of countries than other studies which focus only on direct dependence.

4.3. Socio-economic exposure

Having discussed the fiscal and external exposure in detail, we now move on to analysing the socioeconomic exposure to the low-carbon transition. While we calculate such exposure as the share of employment and wages in sunset industries as we formally showed in Section 3.4, we also take into account the fact that high exposure does not necessarily mean high vulnerability. Countries with high socio-economic exposure to the low-carbon transition that have high levels of income and wealth inequality, a large share of the population below the poverty line and low levels of social protection are more vulnerable than countries where sunset industries are vital for the economy but the population is relatively well protected against job losses. The International Labour Organization compiles data on Social Protection Coverage (SPC) for most of the countries under consideration here (ILO, 2017). The share of the population covered by at least one social protection program may thus provide proxy information on the resilience of countries' most impacted populations.

Fig. 6 presents countries' direct and indirect dependence on sunset industries to generate employment in the vertical axis and wages in the horizontal axis. The Social Protection Coverage (SPC) is presented as the colour of the data points. Countries in the upper right part of the figure are those that depend heavily on sunset industries to both generate employment and pay wages, those in the bottom left pay low wages in these industries and sunset industries are not responsible for generating a large number of employment. The dashed line is the 45-degree line, where the share of wages and employment are the same. Therefore, those

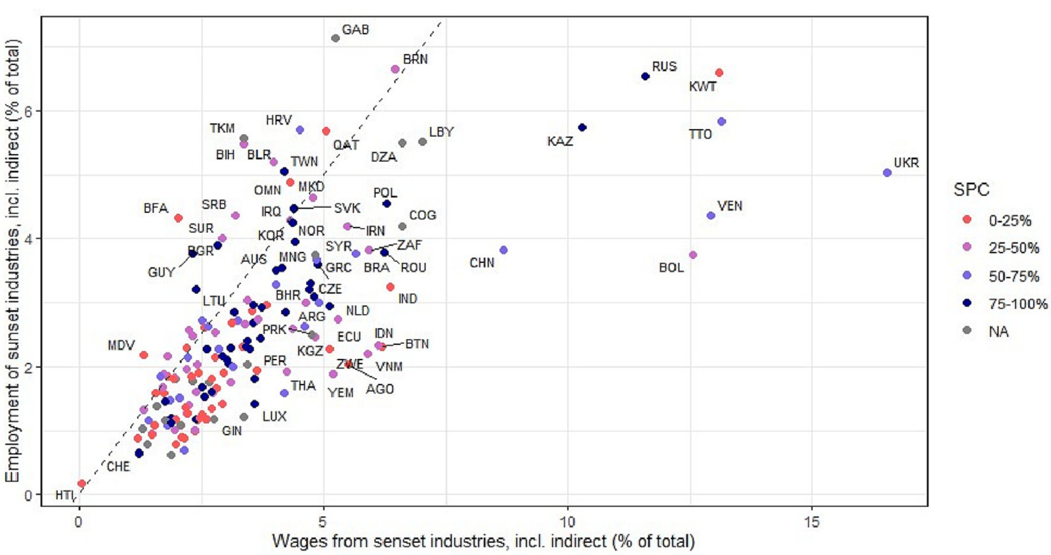

Fig. 6. Countries' socio-economic exposure and vulnerability See Appendix B for country codes and names.

countries in the upper left, despite generating many jobs directly and indirectly in these industries, are not dependent on them in terms of wages, and those in the bottom right present high dependence in terms of wages but not so high in terms of employment.

The most vulnerable economies in the socioeconomic dimension are Kuwait (KWT), Bolivia (BOL), Brunei (BRN), Qatar (QAT), where less than 50% of the population is not covered by any social protection mechanism and there is a high socioeconomic dependence on sunset industries. Possibly Libya (LBY), Algeria (DZA) and Gabon (GAB) are also in this group of countries, but there are no data available for SPC. In these countries, a large share of employment and a large share of wages are directly or indirectly depend on sunset industries, indicating that socioeconomic exposure is high as sunset industries are important as sources of well-paid jobs. Moreover, because only a small part of the population is covered by social protection programs, there might be very serious adverse social consequences of job losses in sunset industries.

In Russia (RUS), Kazakhstan (KAZ), Ukraine (UKR), Trinidad and Tobago (TTO) and China (CHN), despite the high exposure, a large share of the employed population is covered by social protection benefits, implying that vulnerability is not as high as in the group of countries above. Therefore, despite the higher socio-economic exposure, their vulnerability is much lower. Moreover, if we also take into account the capacity of these countries to migrate from sunset industries to green products, measured by the GCP as discussed before, we can affirm that despite the exposure, the socioeconomic risks are also very low, as these countries rank among the most complex countries. This is the case, for example, of Ukraine and China, which are very exposed from a static perspective, but because they have good social protection systems (relatively to the other very exposed countries) and present a high potential to transform their economic structure towards green products, the low-carbon transition tends to impose fewer potential costs for their population. Actually, China is a very special case as it ranks first in the GCP, which means that it is a country with a very high capacity to migrate to green products. Ukraine, despite not having the same level of productive and technological capabilities as China, is also among the countries with the higher GCP (it ranks 50th among more than 200 countries).

5. Multidimensional exposure

A country's particular exposure and vulnerabilities to the low-carbon transition is complex and multi-faceted, thus any meaningful analysis needs to adopt a multi-dimensional approach. With the aim of showing how these different exposures vary across countries, Fig. 7 presents some selected countries' exposure degrees for five indicators discussed before: Net raise of foreign exchange (NXr), Tax revenue (Taxes), Production (Prod), Employment (Empl) and Wages. These countries were chosen not because they are in any special group, but only to illustrate the importance of multidimensional analysis as they present high levels of exposure for different reasons. The solid part of the radar graph is the direct exposure, which accounts only for sunset industries, and the line is the total exposure, which accounts both for the direct and indirect exposure.

The four countries at the top (Kuwait, Russia, Bolivia and Kazakhstan) display high dependence on sunset industries for all variables under consideration. Except for tax revenues in Russia, all variables are close to the maximum across these economies, indicating that they are exposed in all dimensions. There are, however, interesting differences between these countries. In the case of Bolivia, indirect impacts are pertinent to explain the socioeconomic and fiscal exposure (measured by wages and employment dependence), whilst in the case of Kuwait the indirect impacts are almost non-existent (Russia and Kazakhstan are intermediate cases). This result suggests that in Bolivia, the sunset industries are more integrated into the rest of the economy while in Kuwait they pose a high socio-economic danger, but are not much integrated. On the one hand, having less integrated sunset industries is advantageous because a drop in their production will have less systemic impact on other industries, while, on the other hand, this low integration of sunset industries with the rest of the economy indicates that the economy is less diversified and the potential to absorb negative shocks is lower than those economies with more integrated sunset industries. Despite these differences, however, the low-carbon transition may constrain growth in all these economies by exposing them to both balance-of-payments crisis and fiscal and socioeconomic constraints.

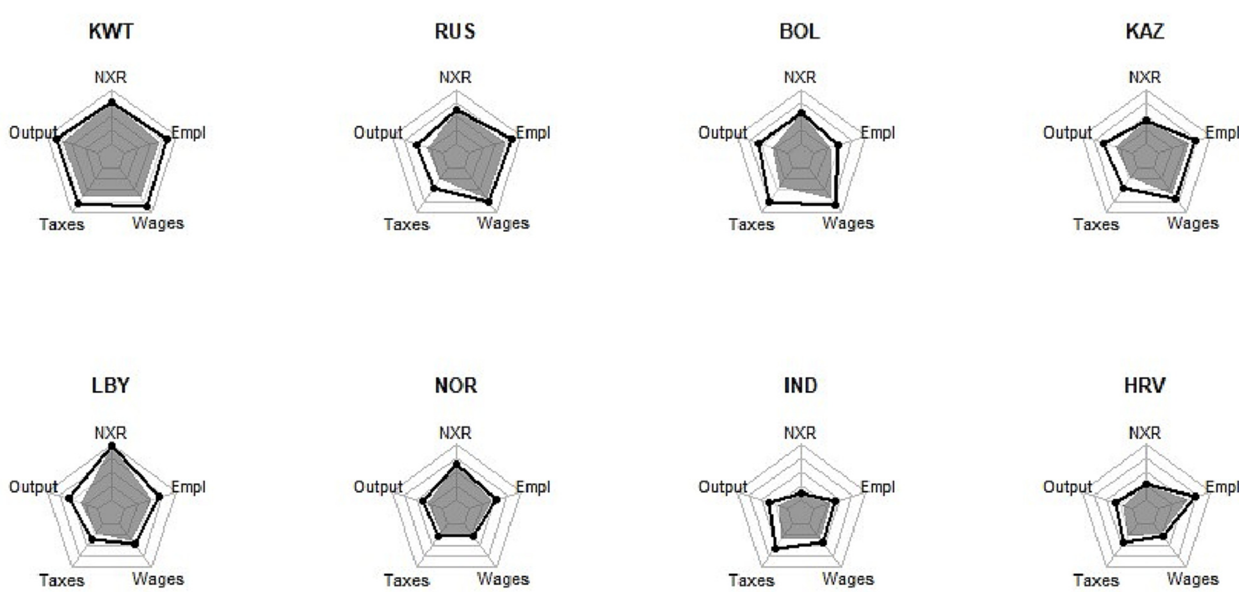

Fig. 7. Selected countries' multidimensional exposure Solids for direct dependence on sunset industries and lines for total dependence (direct and indirect) Max: Net foreign currency revenues (NXr): 75%, Output and Taxes: 40%, Wages: 15%, Employment (Empl): 8%. See Appendix B for country codes and names.

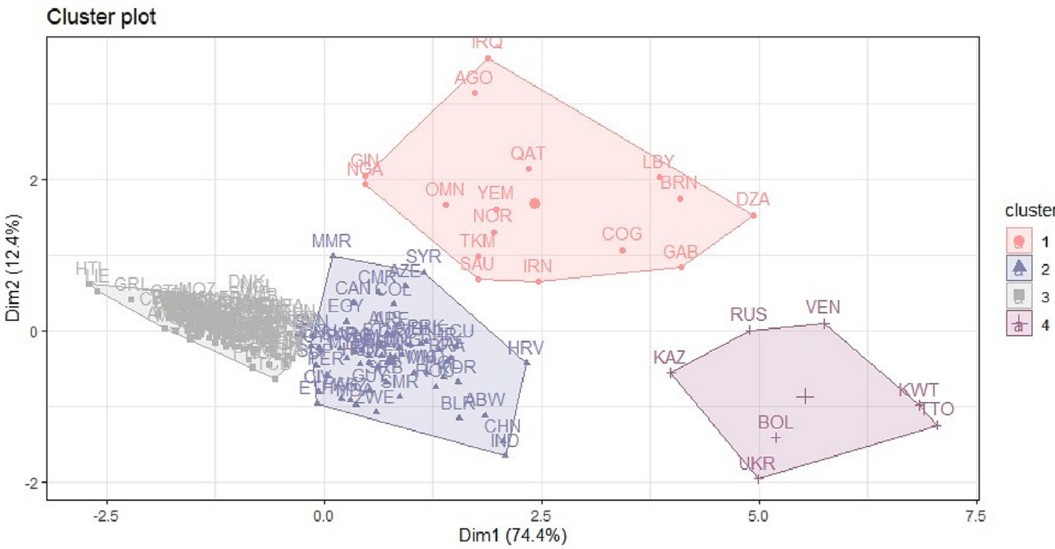

Fig. 8. Cluster of countries according to their exposure See Appendix B for country codes and names.

The two economies in the bottom left (Libya and Norway) also present a high external dependence, but in socioeconomic and fiscal terms they are relatively less dependent on sunset industries (compared with the countries in the top). In these economies, sunset industries are an important source of foreign exchange, but they are not as integrated with the rest of the economy as the other analysed countries, and hence they are only externally exposed. As discussed before, however, they are very different economies in terms of their capacity to promote a structural transformation on their exports. While Libya is a country with low green complexity, Norway is a country with relatively high potential to migrate its exports towards green products, which means that policies for promoting a low-carbon transition tend to have less impact on Norway than on Libya.

Finally, the two economies in the bottom right present a lower external dependence but are relatively more exposed in the other two dimensions (fiscal and socioeconomic). In these economies, sunset industries are not responsible for raising foreign exchange, but they are important either directly (in Croatia) or indirectly (in India) for raising fiscal revenues and for generating employment and paying wages. Therefore, even though the external dimension is not the main concern for them, by analysing other dimensions we see that these are also exposed countries. Because each dimension should be considered separately as external, fiscal and socioeconomic pressures are different across countries, we cannot aggregate these results in a single exposure index. Instead, we need to analyse these exposures in a multidimensional framework.

5.1. Clustering

We next run clustering algorithms on the different dimensions mentioned above in order to determine similarities across countries. Clustering analysis is an important tool to group together countries with similar characteristics, allowing us to identify different groups of countries depending on their exposure to transitional risk. We use hierarchical cluster analysis since it does not require a priori knowledge of the number of clusters, as for example is the case with partitioning algorithms. Hierarchical clustering only requires a dissimilarity measurement between groups of observations, based on the pairwise dissimilarities among observations (Hastie et al. 2017, p. 520). In particular, we construct a dissimilarity matrix based on Euclidean distances and apply a set of agglomerative (bottom-up) strategies. Such strategies start at the bottom, where every country is a separate cluster, and then they recursively merge countries into larger clusters based on the smallest intergroup dissimilarity. We utilise Ward's minimum variance method, which minimises the within-cluster inertia, or error sum of squares. The result is a dendrogram, with each hierarchy level representing disjoint clusters of countries. From the resulting dendrogram structure, however, it is hard to pinpoint the optimal number of clusters. For this reason, we use a combination of statistical heuristics as well as economic intuition, in order to identify the potential clusters.[6]

Fig. 8 presents the four clusters in the first two main components, after reducing the dimension of the dataset via Principal Component Analysis (PCA). Since the dissimilarity matrix cannot contain empty elements, we consider that the share of employment for the few countries where data is not available is equal to the share of wages. Note that as discussed above, this is not a major limitation due to the relatively high correlation of Employment with Wages.

The grey cluster (left-hand side) is composed of countries with lower levels of exposure in general, and hence can be categorised as "low exposed economies". The purple cluster (right-hand side) is composed of countries with the highest exposure. The eight countries discussed in the previous section lie in this group, even though their exposures are due to different dimensions. This group is also composed of countries with low green complexity such as Kazakhstan, Trinidad and Tobago, Bolivia and Venezuela, hence displaying high vulnerability, and countries with higher green complexity such as Russia and Ukraine, hence displaying more resilience. Therefore, although included in the group of high exposure, countries do not present necessarily uniformly high vulnerabilities to the low-carbon transition. Note that this partly occurs due to our choice to focus on 4 clusters. Considering for example a higher number of clusters, Bolivia, Kuwait and Trinidad and Tobago are classified in a separate cluster.

Economies lying in the two clusters in the centre of the space display moderate to high exposure in some dimensions but not in all of them, requiring a more detailed analysis along the different dimensions.

[6] For more details on the choice of method and several robustness checks see the Appendix.

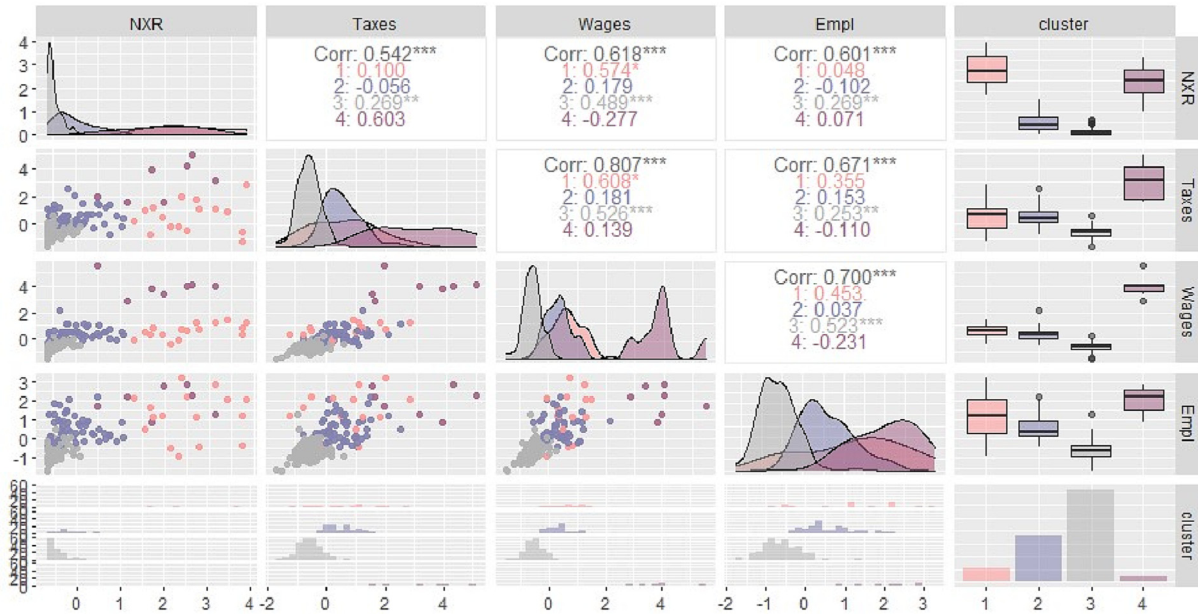

Fig. 9. Distributions of exposure dimensions per cluster.

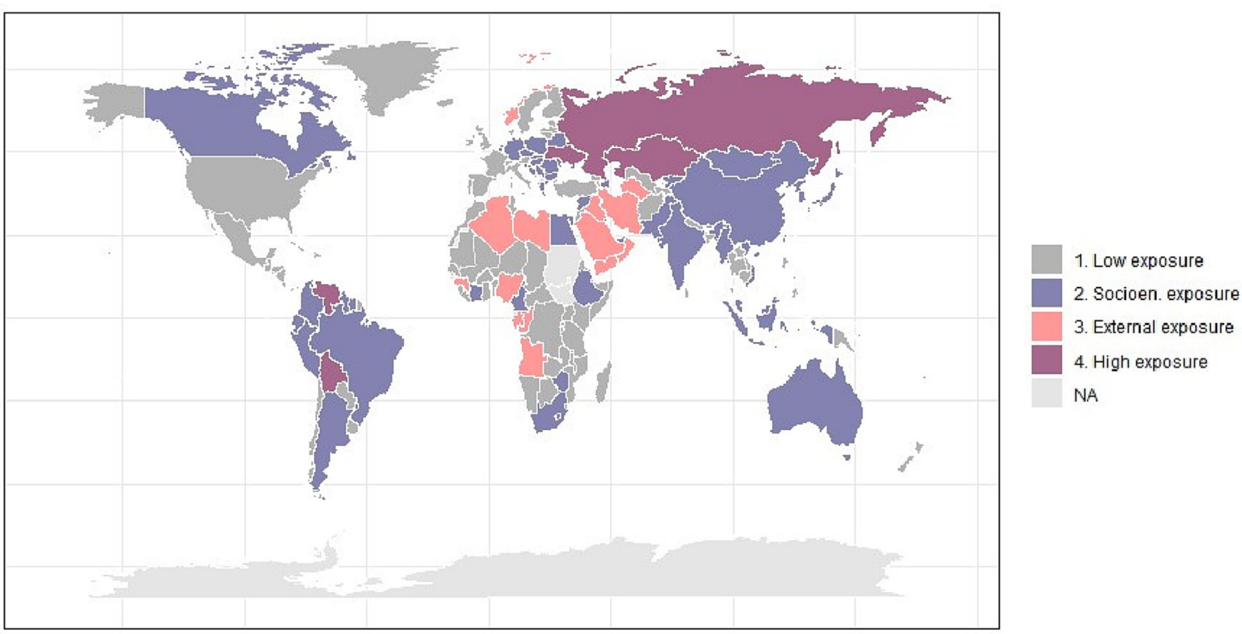

Fig. 10. Countries' exposure by clusters.

Fig. 9 presents the distributions of the different dimensions we are considering in our analysis, within each different cluster. The two central clusters are well defined in terms of the countries' exposure. Countries in grey and purple groups have respectively the lowest and highest average exposure in all dimensions.[7] The red and the blue clusters, however, present a much less clear degree of exposure in general, but when we analyse in terms of the dimensions, they are much more well defined. In the case of the red cluster, the external exposure (measured by the dependence of sunset industries to raise foreign exchange) is close, and sometimes even higher, than the most exposed economies. However, since they are relatively less exposed in the other dimensions, they can be defined as "externally exposed economies". On the other hand, whilst the red cluster presents, in general, a high external exposure, the blue cluster presents a high exposure in the socioeconomic dimension (wages and employment). It means that in these countries low-carbon transition might have relevant socio-economic impacts, especially if they cannot transform the economy and migrate to green industries.

Even though some countries in red present higher external exposure than countries in purple (and vice-versa), as countries in the same group present similarities across all dimensions, we can sum up the relative exposure of each cluster of countries as follows:

[7] Note that there is overlapping across clusters indicating that we can observe countries belonging in other clusters with lower or higher exposure than those of the countries belonging to the low- or high-exposure clusters.

- in grey, countries with low exposure;
- in purple, countries with high exposure in general;
- in red, countries that tend to have higher external exposure; and
- in blue, countries that tend to have high socio-economic exposure.

Fig. 10 presents a world map where countries are divided in these clusters.

6. Conclusion

Analysing developing countries' current exposure and vulnerabilities to the low-carbon transition is crucial to identify appropriate policies in each context. Since green transition will demand large public investments in green infrastructure, subsidies for emerging industries/technologies and investments in social protection among other fiscal expenses, countries with high fiscal vulnerabilities will hardly succeed in the low-carbon transition if public policies do not consider this constraint. Similarly, a large number of countries will need to import inputs and machines to move from emission intensive technologies to green ones. Therefore, countries' external vulnerabilities may also constrain the low-carbon transition if green policies do not account for that.

6.1. Contributions

In order to contribute to the emerging literature on countries' systemic and macroeconomic current exposure and vulnerabilities to the low-carbon transition, this paper has developed a static methodology based on hybrid multi-regional input–output matrices to evaluate the sectoral capability to generate foreign exchange, fiscal revenues, employment and wage income. Our results show that among the countries somewhat dependent on sunset industries, there is a significant variation on the type of this dependence. This implies that using aggregate measures of exposure may mask the true risks involved in the green transition and may hence be misleading. We have therefore abstained from developing such an aggregate exposure index but have rather presented a multi-dimensional analysis of current exposure. We find that even though external exposure mainly arises from a large share of mining activities in the economy, other industries such as petroleum, chemicals and non-mineral metals are generally the main drivers of fiscal exposure, whilst socio-economic exposure is predominantly driven by the indirect impacts of declining sunset industries and therefore displays a great degree of variation among countries.

We have finally complemented our analysis of current exposure with an evaluation of the capabilities of countries to adapt to the constraints brought forward by the low-carbon transition. The combination of high exposure and low productive and technological capabilities or social protection indicates that the country is vulnerable to the low-carbon transition. Using these categorizations, we have shown that while some countries such as China, Kazakhstan and Russia are highly exposed yet not vulnerable due to high green potential and/or strong social protection schemes, other countries, such as Bolivia, Qatar, and Kuwait, have both high exposure and a high vulnerability.

6.2. Policy implications

This paper and its general methodological approach allow us to assess the current multidimensional exposure of a given economy to low-carbon transition policies that affect both the external dynamics (trade and foreign investment) and domestic dynamics (fiscal and socioeconomic stability). Even though this is a static approach, as it does not account for the possibility of countries to move towards sunrise industries, and it presents some technical limitations mainly due to data availability,[8] it brings important insights on the constraints that may emerge, especially for those economies that cannot easily promote structural transformation. Moreover, if we consider the recommendations of Shukla et al. (2022), transition trajectories to keep the Paris Agreement's objectives within reach are extremely steep, and hence this exposure analysis is all the more meaningful as the transition needs to take place in a rapid pace.

On the policy side, several implications follow from this analysis. First, it is clear that carbon-pricing policies alone will not be sufficient to manage the massive structural change necessary for the countries to accomplish their National Determined Contributions (NDCs). If one considers that some sectors will shrink (or even disappear), whilst others will emerge during the transition, carbon price policies might create balance-of-payments and fiscal imbalances, increase unemployment and decrease wage incomes, thus triggering social unrest in many countries. Even though carbon price mechanisms may create incentives to use efficient techniques by promoting large investments to reduce emission-intensity in some sectors, it may not be sufficient if financial constraints bind the transition (Campiglio, 2016; Nasir et al., 2019), which could be the case for countries with high external vulnerability (Gramkow and Porcile, 2022). It may not be sufficient also if fiscal revenues and employment depend disproportionally on sunset industries, which could be the case for countries with high fiscal and socioeconomic vulnerabilities (Jones et al., 2013, Saget et al., 2020).

For the most exposed countries in socio-economic terms, green fiscal stimulus may help mitigate some of the social impacts during the transition process and sustain the emergence of new sectors through appropriate industrial policies. Furthermore, many developing countries have proposed conditional NDCs on their levels of ambitions, depending on the technical and financial assistance of the international community (Kuramochi et al., 2021).

Finally, countries with high socioeconomic and external exposure tend to face a problem of systemic structural adjustment. Attempting to put forward a low-carbon transition within these economies will create imbalances and these imbalances may constrain not only growth and employment but also the transition itself. This may well justify specific international financing and technological transfer programs, such as the Just Energy Transition partnership that was announced at COP26 in the case of South Africa (Houston and Ruppel, 2022). It might also be the case that the early retrofit of high-emission intensive industries may require specific international financing schemes such as the Energy Transition Mechanism of the Asian Development Bank (Citaristi, 2022). These policies, however, need to be applied in wider scales than currently used. The multidimensional exposure analysis thus offers a toolbox to adjust transition policies depending on one country's dependence on sunset industries for stabilising macroeconomic and socioeconomic imbalances.

CRediT authorship contribution statement

Guilherme Magacho: Conceptualization, Methodology, Software, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Etienne Espagne:** Conceptualization, Validation, Investigation, Writing – review & editing, Supervision. **Antoine Godin:** Conceptualization, Methodol-

[8] Appendix A.3 presents a discussion on possible extensions using new sources of data.

ogy, Validation, Investigation, Data curation, Writing – review & editing. **Achilleas Mantes:** Software, Formal analysis, Data curation, Writing – original draft, Visualization. **Devrim Yilmaz:** Methodology, Validation, Formal analysis, Writing – review & editing, Supervision.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table A1
Agglomerative coefficients.

Average	0.96
Single	0.86
Complete	0.97
Centroid	0.88
Ward	0.99

Appendix

A.1. Details on clustering

The set of agglomerative methods that we consider are the single linkage, complete linkage, average linkage, centroid linkage and Ward's minimum variance. We decided to use Ward's minimum variance based on the agglomerative coefficients. Ward's method corresponding coefficient is very high, highlighting its suitability for our analysis (Table A.1).

Moreover, all methods generated relatively similar clusters. The following tanglegram (Fig. A.1) compares the clusters formed by the complete and the Ward's methods. The highlighted linkages indicate the countries that appear in common clusters between the two methods. The continuous, coloured lines in each dendrogram highlight the common clusters that appear at higher levels of hierarchy across the two methods.

More formally, we test for the similarity across the different methods via their pairwise cophenetic correlations, which measure the correlation between the cophenetic dissimilarities derived from two dendrograms. As evident from the cophenetic correlation matrix below, all methods give relatively similar clusters (Table A.2).

As a further robustness check we compute Baker's gamma correlation coefficient for Ward's method vis a vis the other methods, which measures the association between two dendrograms. Again, we find high similarities across dendrograms, with the exception of the centroid method (Table A.3).

Note that almost all values in the cophenetic and Baker's gamma correlation matrices are above 0.5 hence are typically considered significant. We further proceed to an exact p-value analysis of the significance of the two indexes by implementing a permutation test between Ward and the complete method. We choose to compare Ward vs the complete method as the latter has the second highest agglomerative coefficient. We perform a bootstrap analysis

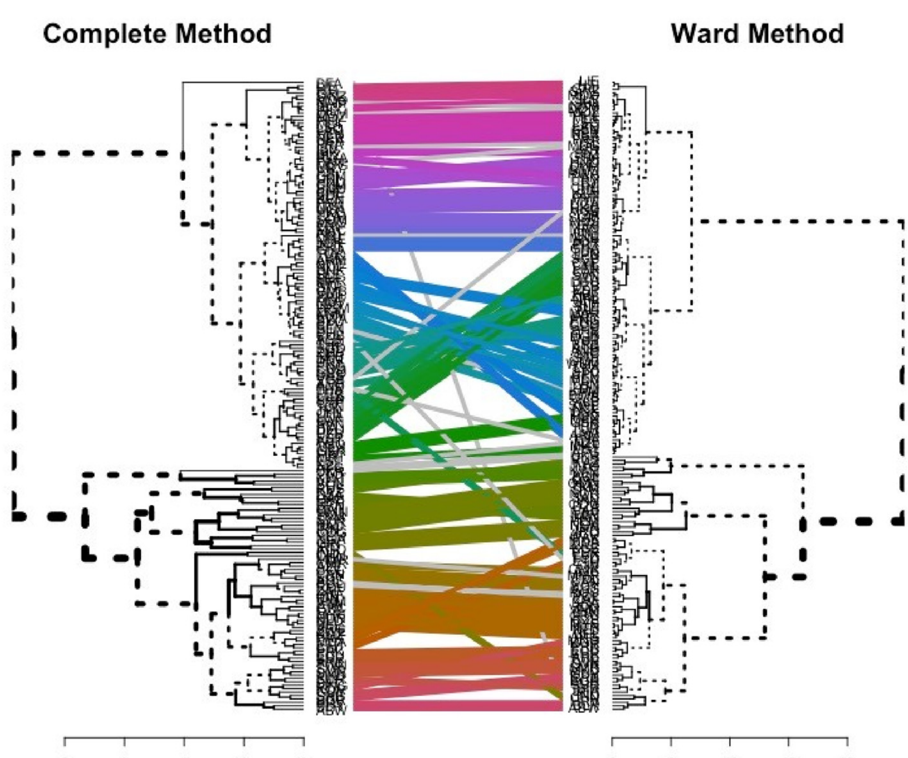

Fig. A1. Tanglegram: Complete vs. Ward similarity.

Table A2
Cophenetic correlation matrix.

	Complete	Single	Average	Centroid	Ward
Complete	1.0				
Single	0.94	1.0			
Average	0.99	0.94	1.0		
Centroid	0.99	0.94	0.99	1.0	
Ward	0.98	0.91	0.98	0.98	1.0

Table A3
Baker's gamma correlation matrix, Ward vs.

Average	0.94
Single	0.83
Complete	0.89
Centroid	0.00
Ward	1.0

(500 samples) to estimate the distributions of the cophenetic and Baker's gamma correlations. We then test the null hypothesis that the correlations of the Ward vs the complete method are 0, i.e. that the two dendrograms are not similar. Under the assumption of asymptotic normality, we reject the hypothesis of non-similarity between the two clusters at the 0.99 confidence interval, for both the cophenetic and Baker's gamma.

To chose the appropriate number of clusters we use a combination of statistical heuristics and economic intuition. In particular, we utilised the NbClust statistical package (Charrad et al., 2014), which provides 30 different indices for the determination of the number of clusters. We then calculated a weighted average of the proposed number of clusters, assuming equal weights for each index. From this analysis the optimal number of clusters obtained is k = 3 (rounded down). Nevertheless, we decided to use k = 4 as it defines the group of high-risk countries more clearly, without distorting the general structure of high, mid and low risk grouping that we also retrieve from 3 clusters (see also Fig. A.2 below).

Lastly, as is common in such clustering exercises, we perform Principal Components Analysis (PCA) and apply k-means clustering on the first two main components. The main benefit of PCA is that a small number of principal components can pick up the largest variance in the data. Hence, visualising the data on the two main components allows us to identify the variables that contribute the most to the (dis)similarities across countries. We use k-means as it uses the same objective function as the Ward method and since we fix the number of clusters (k = 4), we can now implement partitioning methods. This serves as a further robustness check of our hierarchical clustering results. The PCA results are presented below. Fig. A3 presents the contribution of each variable in the first two principal components.

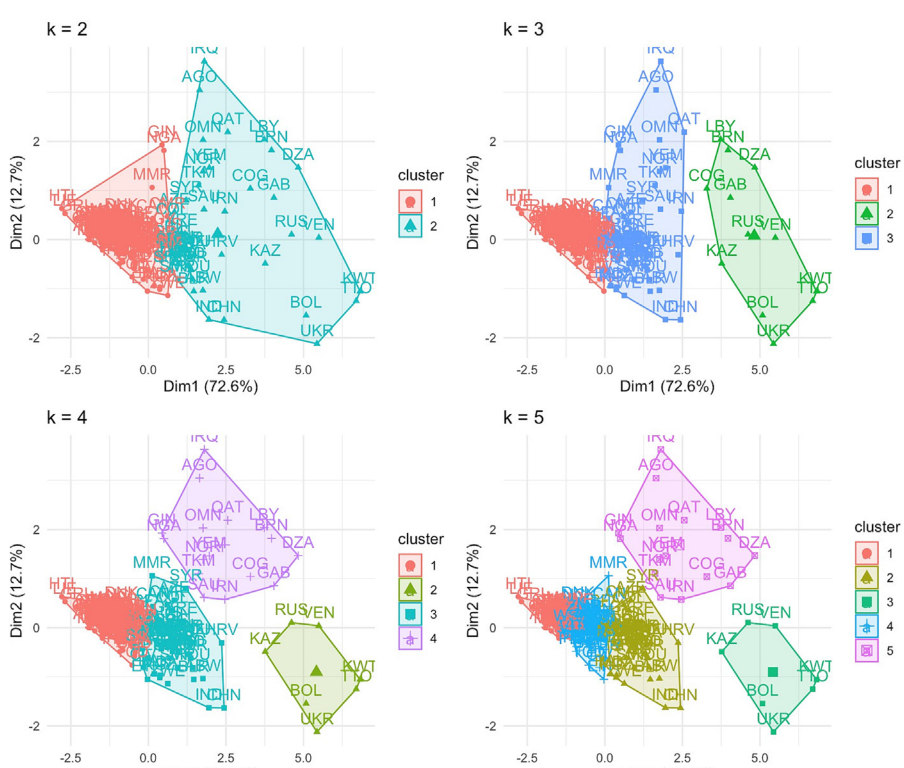

Fig. A2. K-means clusters.

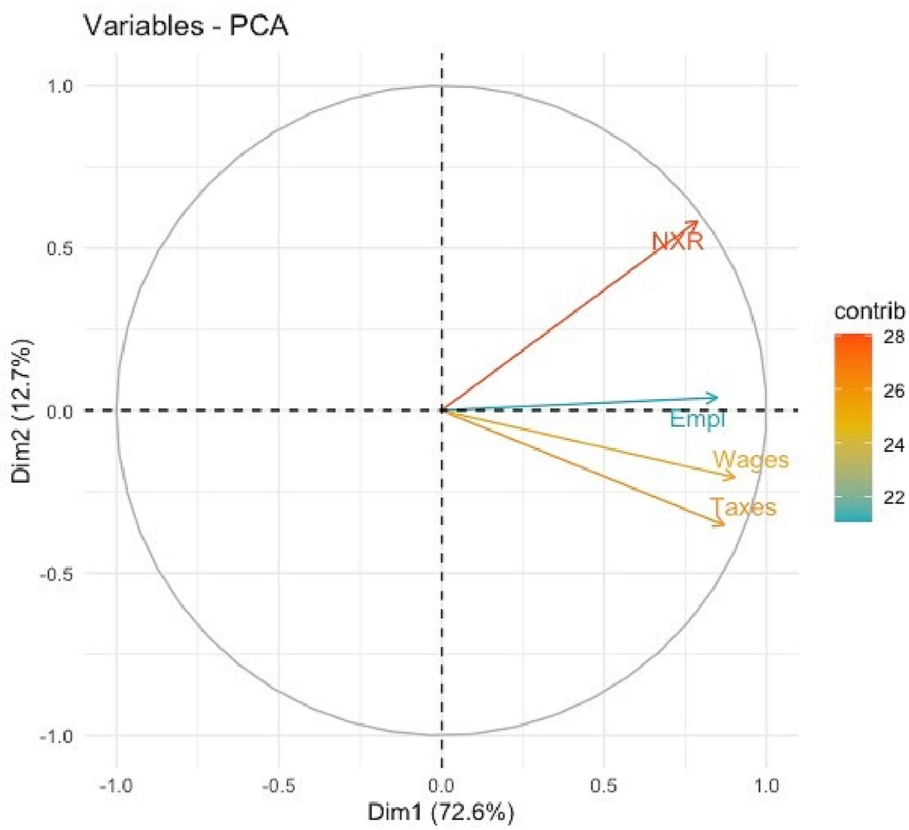

Fig. A3. PCA components.

A.2. Countries' codes and names

Table A.4.

Table A4
Countries' codes and names.

Code	Name	Code	Name	Code	Name	Cade	Name
AFG	Afghanistan	CIV	Cote d'Ivoire	LBN	Lebanon	RWA	Rwanda
ALB	Albania	PRK	Korea, D. P. R.	LSO	Lesotho	WSM	Samoa
DZA	Algeria	COD	Congo, D. R.	LBR	Liberia	SMR	San Marino
AND	Andorra	DNK	Denmark	LBY	Libya	STP	Sao Tome and Principe
AGO	Angola	DJI	Djibouti	LIE	Liechtenstein	SAU	Saudi Arabia
ATG	Antigua and Barbuda	DOM	Dominican Rep.	LTU	Lithuania	SEN	Senegal
ARG	Argentina	ECU	Ecuador	LUX	Luxembourg	SRB	Serbia
ARM	Armenia	EGY	Egypt, Arab Rep.	MAC	Macao SAR, China	SYC	Seychelles
ABW	Aruba	SLV	El Salvador	MDG	Madagascar	SLE	Sierra Leone
AUS	Australia	ERI	Eritrea	MWI	Malawi	SGP	Singapore
AUT	Austria	EST	Estonia	MYS	Malaysia	SVK	Slovak Republic
AZE	Azerbaijan	ETH	Ethiopia	MDV	Maldives	SVN	Slovenia
BHS	Bahamas, The	FJI	Fiji	MLI	Mali	SOM	Somalia
BHR	Bahrain	FIN	Finland	MLT	Malta	ZAF	South Africa
BGD	Bangladesh	FRA	France	MRT	Mauritania	ESP	Spain
BRB	Barbados	PYF	French Polynesia	MUS	Mauritius	LKA	Sri Lanka
BLR	Belarus	GAB	Gabon	MEX	Mexico	SUR	Suriname
BEL	Belgium	GMB	Gambia, The	MCO	Monaco	SWZ	Eswatini
BLZ	Belize	GEO	Georgia	MNG	Mongolia	SWE	Sweden
BEN	Benin	DEU	Germany	MNE	Montenegro	CHE	Switzerland
BMU	Bermuda	GHA	Ghana	MAR	Morocco	SYR	Syrian Arab Rep.
BTN	Bhutan	GRC	Greece	MOZ	Mozambique	TWN	Taiwan, China
BOL	Bolivia	GRL	Greenland	MMR	Myanmar	TJK	Tajikistan
BIH	Bosnia and Herzegovina	GTM	Guatemala	NAM	Namibia	THA	Thailand
BWA	Botswana	GIN	Guinea	NPL	Nepal	MKD	North Macedonia

(*continued on next page*)

Table A4 (*continued*)

Code	Name	Code	Name	Code	Name	Cade	Name
BRA	Brazil	GUY	Guyana	NLD	Netherlands	TGO	Togo
VGB	British Virgin Islands	HTI	Haiti	NCL	New Caledonia	TTO	Trinidad and Tobago
BRN	Brunei Darussalam	HND	Honduras	NZL	New Zealand	TUN	Tunisia
BGR	Bulgaria	HKG	Hong Kong SAR, China	NIC	Nicaragua	TUR	Turkey
BFA	Burkina Faso	HUN	Hungary	NER	Niger	TKM	Turkmenistan
BDI	Burundi	ISL	Iceland	NGA	Nigeria	UGA	Uganda
KHM	Cambodia	IND	India	NOR	Norway	UKR	Ukraine
CMR	Cameroon	IDN	Indonesia	PSE	West Bank and Gaza	ARE	United Arab Emirates
CAN	Canada	IRN	Iran, Islamic Rep.	OMN	Oman	GBR	United Kingdom
CPV	Cabo Verde	IRQ	Iraq	PAK	Pakistan	TZA	Tanzania
CYM	Cayman Islands	IRL	Ireland	PAN	Panama	USA	United States
CAF	Central African Rep.	ISR	Israel	PNG	Papua New Guinea	URY	Uruguay
TCD	Chad	ITA	Italy	PRY	Paraguay	UZB	Uzbekistan
CHL	Chile	JAM	Jamaica	PER	Peru	VUT	Vanuatu
CHN	China	JPN	Japan	PHL	Philippines	VEN	Venezuela, R. B.
COL	Colombia	JOR	Jordan	POL	Poland	VNM	Vietnam
COG	Congo, Rep.	KAZ	Kazakhstan	PRT	Portugal	YEM	Yemen, Rep.
CRI	Costa Rica	KEN	Kenya	QAT	Qatar	ZMB	Zambia
HRV	Croatia	KWT	Kuwait	KOR	Korea, Rep.	ZWE	Zimbabwe
CUB	Cuba	KGZ	Kyrgyz Republic	MDA	Moldova	RWA	Rwanda
CYP	Cyprus	LAO	Lao PDR	ROU	Romania	WSM	Samoa

A.3 Extensions

The sectoral aggregation in the EORA-26 does not allow us to identify precisely what the sunset industries are in each country but only the broad sectors where these industries are located. With the aim of reducing this bias, we used other data sources to estimate the share of effective sunset industries within these sectors, but the technical coefficients do not account for differences within these sectors. One possibility of refining these results is using more disaggregated Input-output tables. Shapirp (2021), for example, uses the EXIOBASE, which disaggregates 48 countries into 163 industries to measure CO2 intensity for each international and intra-national trade flow in the global economy. This dataset, as well as all other multiregional tables available cover only a few developing economies. Therefore, an extension of this analysis can be made using either country tables or MRIO that covers fewer countries but have more detailed sectoral coverage.

Besides extending the work developed here using more disaggregated data, it would be interesting to analyse countries' exposures in different dimensions, such as the exposure of countries' financial system to the low-carbon transition. Sectoral financial data allows us to identify the financial exposure and sensitivity of different sectors to low-carbon transition shocks. Godin and Hadji-Lazaro (2021) developed a methodology to identify the demand-induced transition vulnerabilities and applied it to South Africa, where data on sectoral assets, equities and liabilities are available for 2018 on the Annual Financial Statistics Survey for 190 industries. Using an input–output approach, the authors identify not only those industries with the highest financial fragility, but also how this fragility may propagate through the industrial network using Cahen-Fourot et al. (2020)'s approach. It is thus possible to analyse the financial exposure of industries within different countries based on their location in the industrial network and on the overall structure of sectoral costs in this network.

The analysis of the external exposure in this paper is based only on trade flows and the dependence on sunset industries considers only their importance to raise foreign exchange through exports. Nevertheless, Foreign Direct Investments (FDI) are also an important source of foreign exchange for some countries, easing or relaxing balance-of-payment constraints at times and reinforcing trade flows at others. Again, the lack of sectoral data is the main constraint for this type of analysis. FDI inflows are available for developed economies for 12 sectors at the OECD Stat, and some developing countries such as Colombia have these data with similar disaggregation. Nevertheless, data are not available for most of the developing economies, and hence one cannot account yet for this aspect when analysing external exposure.

Another possible extension is related to fiscal exposure. One of the assumptions in our study is that wage and profit taxation is the same across sectors for a given country, and the sectoral fiscal dependence is given either by differences in product taxation (sales and VAT) or by differences in the composition of income distribution, (wages, profits and other incomes). There might be, however, countries where profits and wages are taxed at lower rates in some sectors, which we cannot account for here. In some countries, this data is available disaggregated at the sectoral level, which allows us to identify more precisely fiscal exposure. The Federal Revenue of Brazil (RFB, in Portuguese), for example, provides disaggregated tax data for 87 industries. These data allow us to identify what the actual direct contribution of each sector to fiscal revenue is and using our input–output framework, we can then calculate the indirect dependence of fiscal revenues on each of these industries. Once more detailed data for other countries are also available, we can thus estimate more precisely both the direct and indirect sectoral tax contribution of sunset industries, and hence countries' fiscal exposure.

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