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Capital stranding cascades: The impact of decarbonisation on productive asset utilisation

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ABSTRACT

A timely low-carbon transition will require a significant decline in fossil fuel production and consumption. This in turn exposes the rest of economic sectors to the risk of reduced usability of physical capital stocks via international production network linkages. We propose and apply a simple measure to assess the extent to which fossil shocks might trigger underutilisation of capital stocks across countries and productive sectors ('stranding multipliers'). Our results highlight the relevance of supply-side transition risks. First, among all productive activities, the global fossil sector exhibits the highest stranding multiplier on the rest of the economic system. Second, some of the most exposed sectors are downstream activities, mainly affected by second-round effects. Third, we rank countries according to their external stranding potential, finding France, Australia and Slovakia at the top, and the USA, Italy and China at its bottom. Finally, we rank countries according to their exposure to stranding risk and analyse more in depth the origins and transmission channels of the stranding links affecting some of the most exposed countries (USA, China and Germany).

1. Introduction

Achieving the climate-related objectives of the Paris Agreement (UNFCCC, 2016) will require a substantial decline in the global production and consumption of fossil fuels (SEI et al., 2020). Considering the obstacles in the implementation of demand-side climate policies (e.g carbon taxes), several authors have argued in favour of introducing complementary supply-side policies aimed at limiting the extraction of fossil fuels (Harstad, 2012; Asheim et al., 2019; Erickson et al., 2018).

Modern economic systems are still heavily reliant on fossil fuels (IEA, 2020b). Many productive processes use raw or refined fossil fuels directly as a material input or to produce heat. While competitive low-carbon alternatives exist in some activities such as electricity generation (Lazard, 2020), high-carbon incumbent technologies still represent the most convenient option in a large range of economic sectors, e.g. transport, chemicals, steel (IEA, 2020a). The problem is exacerbated by the existence of a substantial amount of long-lived capital stock (e.g. coal/gas electricity plants and blast furnaces). The greenhouse gas emissions that would result from the full utilisation of these physical assets until their natural end of life would be incompatible with respecting a temperature ceiling of 1.5–2 °C and lead to some asset stranding (Tong et al., 2019; Pfeiffer et al., 2018; IEA, 2020a). Stranding of physical capital assets can take three main forms: (i) premature decommissioning of assets; (ii) reduced utilisation of assets; (iii) costs linked to the retrofitting of assets. We here define stranding as loss of capital utilisation, following contributions from numerical integrated assessment modelling (Cui et al., 2019; Johnson et al., 2015; Fofrich et al., 2020) and analytical modelling (Baldwin et al., 2020; Coulomb et al., 2019; Rozenberg et al., 2020).

It is reasonable to expect supply-side transition-related disruptions not to be limited to sectors directly employing fossil fuels in their productive processes. These activities provide in turn indispensable

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intermediate inputs to more downstream sectors producing consumption goods and services. Through production network linkages, the defossilisation process could cause substantial disruptions to the entire economic system. The relevance of sectoral disruptions in triggering macroeconomic fluctuations via production networks is being thoroughly investigated in the economics literature (see Gabaix, 2011; Acemoglu et al., 2012; Carvalho and Tahbaz-Salehi, 2019; Joya and Rougier, 2019, among others). However, production network analysis has been so far largely excluded from the expanding literature trying to assess the risk of asset stranding and the wider macro-financial implications of moving to a carbon-free economy (Caldecott, 2018; van der Ploeg and Rezai, 2020; Semieniuk et al., 2021). Most of the contributions on the topic have focused on the stranding of fossil reserves (McGlade and Ekins, 2015; Mercure et al., 2018, 2021), on knock-on financial effects (Battiston et al., 2017) or on the role of policies and institutions in mitigating climate-related risks (Campiglio et al., 2018). Sectoral dependencies have been incorporated in a limited number of works (e.g. Vermeulen et al., 2018; Allen et al., 2020) but without considering physical capital stocks. As a result, we currently do not have methods to study how a decrease in fossil fuel inputs would strand capital stocks in the rest of the productive system.

We contribute to filling this research gap by providing a systemic perspective on the supply-side risk of physical capital stranding. We do so by developing a simple methodology rooted in input–output analysis and applying it to a multi-regional production network database. This allows us to compute cross-sectoral and cross-boundary 'marginal stranding multipliers'. These multipliers provide a monetary estimate of the exposure of sectoral capital stocks to the risk of becoming unutilised due to a marginal loss in primary inputs (i.e. a $1 reduction in labour or capital inputs to production) employed in the fossil sector of a country, including both direct and indirect effects. Following Blöchl et al. (2011), Cahen-Fourot et al. (2020) and others, we treat input–output linkages (or stranding linkages, in our case) as the edges of a directed weighted network. Through a disaggregation of the multipliers into distinct rounds of effects, we construct cascading networks to study how fossil stranding propagates within the international production system. Given our methodological grounding, our stranding multipliers should be interpreted as a measure of *exposure* to the risk of becoming stranded, and not as a measure of capital actually becoming stranded.[1]

Our results offer several interesting insights.[2] First, we compare the stranding multipliers of fossil industries with the ones of other productive sectors. We find that, while some other sectors (e.g. real estate and waste) exhibit higher total marginal multipliers due to their high sectoral capital intensity, the fossil sector is the one with the highest external stranding multiplier (i.e. the marginal stranding potential on all other sectors). Second, assuming global productive sectors, we study how fossil stranding propagates within the production network and rank productive activities according to their exposure to it. Among the most exposed sectors, we find some that are not significantly affected by *direct* stranding links from the fossil sector but are instead exposed to *indirect* cascading effects. These include public administration, real estate, land transportation, and others. These results support our intuition regarding potential systemic effects driven by defossilisation involving also more downstream activities. Third, we analyse national marginal stranding multipliers and disaggregate them according to their destination. Given the nature of the shock we assume, the international ranking of stranding multipliers does not depend on the absolute relevance of the country as a fossil producer or exporter. Rather, results are driven by (i) for what sectors extracted fossil fuels are used (e.g. domestic use vs export); (ii) their capital intensity. We find France, Australia and Slovakia to have the highest external marginal stranding multipliers; and the USA, Italy and China to have the lowest. Finally, we flip the perspective and study the extent to which countries are exposed to (rather than creating) capital stranding risks. We perform a more detailed analysis of the exposure for a selection of countries (USA, China and Germany), isolating the origins and network transmission channels affecting the most exposed sectors of these countries. We find the US to be exposed to a limited number of very strong stranding links towards Canada and Mexico, with a particularly relevant stranding channel affecting the US public administration via the US coke and refinery industry. Chinese exposure is slightly lower in absolute terms and much more diversified, although Australia and Taiwan stand out as the most relevant origins of risk. Finally, Germany is exposed to several other European countries and their refinery industries in particular.

The remainder of the paper is structured as follows. Section 2 describes our methodology and the source of the data we use. Section 3 presents a first set of results where we consider only global sectors. Section 4 adopts a more granular approach to focus on cross-boundary stranding. Section 5 performs a more detailed exposure analysis for the USA, China and Germany, which are among the most exposed countries to supply-side fossil stranding risk. Section 6 discusses limitations and future avenues of research. Finally, Section 7 concludes.

2. Methodology and data

This section presents our methodological approach. First, we explain the method to compute our matrix of 'marginal stranding multipliers'. Second, we discuss how we distinguish among rounds of effects and create 'stranding cascades'. Finally, we present our data sources.

2.1. The matrix S of sectoral stranding multipliers

Fig. 1 offers a stylised representation of a multi-regional Input–Output (MRIO) table (Miller and Blair, 2009). Each sector of each country appears twice in the table. First, it appears as a producer of goods and services (on the rows). Goods and services can be then purchased by other firms to be used as intermediate inputs in further production processes, or be consumed by households, firms or governments as final demand items. Second, it appears as a user of inputs (on the columns). These inputs can take the form of intermediate inputs purchased from other firms or of value added items such as compensation of employees, consumption of fixed capital and gross operating surplus. The $n \times n$ square matrix recording the transactions of goods and services among all n productive sectors is the inter-industry matrix $\mathbf{Z}$ (in grey in Fig. 1). The $n \times 1$ column vector $\mathbf{f}$ represents final demand, while the $1 \times n$ row vector $\mathbf{v}$ represents value added items.

For the input–output table to be balanced, total supply of each industry $\mathbf{x}^T = \mathbf{i}^T\mathbf{Z} + \mathbf{v}$ must be equal to its total use $\mathbf{x} = \mathbf{Z}\mathbf{i} + \mathbf{f}$, where $\mathbf{i}$ is a $n \times 1$ column vector of ones[3] and ^{T} denotes the matrix transposition. In other words, the sum of all flows over a row (total industry output broken down by type of use, i.e. intermediate use and final demand) must equal the sum over the corresponding column (total industry input broken down by 'source', i.e. other industries and value added items).

Sectoral dependencies in IO tables are often studied via the Leontief model (Leontief, 1951). However, the Leontief demand-side approach does not fit well with the supply-side nature of our research question (i.e. what is the stranding effect of a reduction of fossil inputs). We hence choose to employ the supply-side model first proposed by Ghosh

[1] A dynamic complete risk assessment would include also other vulnerability dimensions, such as the sensitivity of economic sectors (e.g. the composition of their capital stocks) and their adaptive capacity (e.g. their ability to innovate, retrofit existing stocks or substitute away from fossil-intensive intermediate inputs).

[2] The code to replicate our results and charts is available at https://github.com/ecampiglio/capital_stranding_cascades.

[3] Pre-multiplying a matrix by $\mathbf{i}^T$ returns its column sum; post-multiplying a matrix by $\mathbf{i}$ returns its row sum.

Inter-industry matrix (Z)		Country 1		Country 2		Final demand (f)	Total use (x)
		Sector A.1	Sector B.1	Sector A.2	Sector B.2		
Country 1	Sector A.1	A.1 products used by A.1	A.1 products used by B.1	A.1 products used by A.2	A.1 products used by B.2	Consumption of A.1 products	Intermediate production + Final demand
	Sector B.1	B.1 products used by A.1	B.1 products used by B.1	B.1 products used by A.2	B.1 products used by B.2	Consumption of B.1 products	
Country 2	Sector A.2	A.2 products used by A.1	A.2 products used by B.1	A.2 products used by A.2	A.2 products used by B.2	Consumption of A.2 products	
	Sector B.2	B.2 products used by A.1	B.2 products used by B.1	B.2 products used by A.2	B.2 products used by B.2	Consumption of B.2 products	
Value added (v)		Value added in A.1	Value added in B.1	Value added in A.2	Value added in B.2		
Total supply ($\mathbf{x}^T$)		Intermediate consumption + Value added					

Fig. 1. A stylised multi-regional input–output table.

(1958) instead. While the Leontief model calculates the matrix $\mathbf{A}$ of technical input coefficients, the Ghosh model defines a matrix $\mathbf{B} = \hat{\mathbf{x}}^{-1}\mathbf{Z}$ of output *allocation* coefficients (where $\hat{\mathbf{x}}$ is the diagonal matrix of the output vector $\mathbf{x}$), whose elements represent the allocation of the output of a sector to all other sectors. In other words, each element b_{ij} quantifies the share of industry i's output that is used by industry j. The Ghosh matrix $\mathbf{G}$ is then defined as $\mathbf{G} = (\mathbf{I} - \mathbf{B})^{-1}$.

For convenience, we transpose $\mathbf{G}$ to be able to read the effects of changes in sectoral primary inputs over the columns of $\mathbf{G}^T$ (similarly to the Leontief matrix $\mathbf{L}$). Each element $g_{i,j}$ of $\mathbf{G}^T$ describes the change in output $\mathbf{x}$ in sector i that would result from a marginal change of primary inputs flowing into sector j. In other words, an increase (decrease) of one monetary unit of primary inputs contributing to production in sector j will increase (decrease) the output of sector i by an amount equal to $g_{i,j}$, where $g_{i,j}$ includes both direct and indirect effects. 'Primary inputs' refers to any item appearing on the rows below the inter-industry matrix. Traditionally, this has been meant to represent compensation of employees (and thus labour input) but, more generally, it can be used to represent any form of societal effort put in producing the output of a specific sector, as represented by factor payments.

We then combine $\mathbf{G}^T$ with sectoral data of physical capital stocks k. We define $\kappa_i = k_i/x_i$ as the capital intensity of sector i, where x is the total output of the sector. By multiplying the diagonalised form of the vector of capital intensities by $\mathbf{G}^T$, we find the matrix $\mathbf{S}$ of asset stranding multipliers $\mathbf{S} = \hat{\boldsymbol{\kappa}}\mathbf{G}^T$.[4] Fig. 2 offers a stylised representation of the $\mathbf{S}$ matrix. Each element s_{ij} represents the change in the utilisation of capital in sector i triggered by a marginal change of primary inputs used by sector j. For our purposes, the elements of $\mathbf{S}$ define the amount of capital stock of a sector i that could become stranded because of a marginal decrease in the primary inputs used in the production of goods and services of another sector j (e.g. fossil fuels). The column sum of matrix $\mathbf{S}$ gives a measure of the total amount of stranded physical assets resulting from a marginal reduction of primary inputs in a sector j. Similarly, we can interpret the sum of the rows of $\mathbf{S}$ as the exposure of a sector i to stranding risk (i.e. the loss in capital utilisation resulting from a marginal loss in primary inputs used in all productive sectors). Table 1 summarises the key terms and concepts introduced in this article for the analysis of stranding effects.

The Ghosh approach is unsuited to analyse the causal effects of large-scale supply bottlenecks (e.g. in the aftermath of natural disasters). Limitations include the assumptions of perfect elasticity of demand in reacting to changes in supply and of perfect substitutability among input factors (Oosterhaven, 1988; Dietzenbacher, 1997; Galbusera and Giannopoulos, 2018). However, it can be usefully employed to describe and compare economic structures and the relative economic/environmental importance of sectors (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). Our results should thus be interpreted uniquely as stranding effects at the margin, i.e. as the exposure of countries and sectors to the risk of physical capital stranding following a marginal shock in the fossil sector. They do not offer causal predictions on what the dynamic stranding effects of a low-carbon transition will be. Rather, they provide valuable insights on the productive structure of nations at a point in time and, more specifically, on the relevance of fossil sectors in keeping downstream capital stocks in operation. Our approach is, therefore, a diagnostic methodology and does not aim at being predictive.

2.2. Cascade networks

The stranding multipliers in $\mathbf{S}$ contain all direct and indirect stranding effects resulting from a change in primary inputs of a productive sector. To better understand these results, it is useful to investigate how stranding propagates through the economic system, distinguishing the direct effects of the initial impulse from the following indirect inter-industry responses. For this purpose, we make use of the fact that the $\mathbf{G}$ matrix can be approximated by a power series: $\mathbf{G} = (\mathbf{I} - \mathbf{B})^{-1} = \lim_{n\to\infty}(\mathbf{I} + \mathbf{B} + \mathbf{B}^2 + \cdots + \mathbf{B}^n)$ (Miller and Blair, 2009). Each element of the series can be interpreted as one round of inter-industry production responses resulting from an exogenous supply change. These rounds should not be interpreted as taking place at real time intervals. Rather, they indicate the successive steps through which initial impulses propagate within the productive system via sectoral interdependencies. The analysis of the power series is common in the input–output literature and is otherwise known as *production layer decomposition* (Lenzen and Crawford, 2009). This sequential perspective has been for instance applied to the allocation of environmental pressure responsibility in global value chains (Piñero et al., 2019). We instead perform a *stranding layer decomposition* analysis, where the power series steps should be understood as stranding allocation steps. We focus on the first few

[4] This definition of stranding multipliers assumes a linear relationship between production and capital utilisation: for a marginal output loss of \$1, the stranded capital stock corresponds to the capital intensity of the respective sector. In other words, we assume constant returns to scale.

Matrix S		Country 1		Country 2		Stranding exposure
		Sector A.1	Sector B.1	Sector A.2	Sector B.2	
Country 1	Sector A.1	$s_{A1,A1}$	$s_{A1,B1}$	$s_{A1,A2}$	$s_{A1,B2}$	Total A.1 stranding exposure
	Sector B.1	$s_{B1,A1}$	$s_{B1,B1}$	$s_{B1,A2}$	$s_{B1,B2}$	Total B.1 stranding exposure
Country 2	Sector A.2	$s_{A2,A1}$	$s_{A2,B1}$	$s_{A2,A2}$	$s_{A2,B2}$	Total A.2 stranding exposure
	Sector B.2	$s_{B2,A1}$	$s_{B2,B1}$	$s_{B2,A2}$	$s_{B2,B2}$	Total B.2 stranding exposure
Stranding multiplier		Total stranding from A.1	Total stranding from B.1	Total stranding from A.2	Total stranding from B.2	

Fig. 2. A stylised representation of the **S** matrix of stranding multipliers.

Table 1
Key concepts used for the analysis of asset stranding.

Concept	Interpretation
Marginal loss in primary inputs	$1 reduction in labour or capital inputs to production in a given sector; also referred to as 'marginal shock'[a]
Total stranding multiplier	Monetary value of the capital stock at risk of becoming unutilised in all sectors of the economy due to a marginal loss in primary inputs in a given originating sector
External stranding multiplier	Stranding multiplier of a sector on all other sectors, excluding the originating sector itself
Total stranding exposure	Monetary value of the capital stock at risk of becoming unutilised in a given target sector due to a marginal loss in primary inputs in all sectors of the economy
External stranding exposure	Exposure of a sector to all other sectors, excluding the target sector itself
Direct stranding effects	Stranding risk arising through direct trade relations with the originating sector; also referred to as 'first-round effects'
Indirect stranding effects	Stranding risk arising through indirect inter-industry trade relations with the originating sector; can be distinguished by the number of intermediate steps in the chain of inter-industry exchange (e.g 'second-round effects' have one intermediate step)

[a]In the Ghosh model, a $1 loss in primary inputs is equivalent to a $1 loss in output of a sector, as all inputs (primary and intermediate) are assumed perfect substitutes.

rounds of effects, which are the most likely to actually take place in the short term, before longer-term dynamic adjustments trigger structural changes our static framework is not able to capture. This allows us to partially offset the limitation of the Ghosh model described in the previous section.

We hence rewrite $\mathbf{S} = \hat{\boldsymbol{\kappa}}\mathbf{G}^T = \lim_{n\to\infty} \hat{\boldsymbol{\kappa}}(\mathbf{I} + \mathbf{B} + \mathbf{B}^2 + \cdots + \mathbf{B}^n)^T$ to disentangle the direct and subsequent indirect stranding effects caused by a fossil supply shock. This decomposition allows us to analyse the distribution of stranding effects over the individual rounds and to identify which sectors are directly exposed to fossil stranding disruptions and which are more indirectly affected via production network adjustments (i.e. in later stages of the power series).

Bearing in mind that stranding multipliers in **S** are the sum of individual stranding channels cascading gradually through the economic system, the power series perspective allows us to increase the resolution of our analysis even further. In particular, we can identify the most important stranding channels by sequentially isolating the strongest linkages from round to round. This can be used to construct graphs that can be interpreted as weighted directed networks. We employ this approach to generate two kinds of networks. First, we study how an initial shock in the fossil sector propagates through the economic system by isolating the dominant stranding cascades it creates. We refer to these graphs as 'cascade networks'. Second, we look at the opposite direction and investigate the exposure of particular sectors to fossil stranding by identifying the most important direct and indirect stranding channels affecting them. The resulting graphs are called 'exposure networks'.

For the cascade networks, we start by placing the fossil sector at the origin of the network, assuming a marginal unitary decrease in its primary inputs as the initial stranding shock. Then we identify the sectors most directly affected by this shock (i.e. in the first round of the stranding power series), given by the highest values of the originating fossil sector's column in the $\hat{\boldsymbol{\kappa}}\mathbf{B}^T$ matrix. Only the top q sectors are retained and placed in the first layer of the network, with the edge weights corresponding to the value of the direct stranding link. The next layer is obtained by repeating this procedure for each sector of the first layer, taking into account that the input loss in these sectors will be lower than one and a function of their relation to the originating sector, as given by the **B** matrix of output allocation coefficients.[5] This is done by simply re-weighting the respective sector's direct stranding links (i.e its column in the $\hat{\boldsymbol{\kappa}}\mathbf{B}^T$ matrix) by its loss of intermediate inputs from the fossil sector according to the corresponding fixed allocation coefficient in the $\mathbf{B}^T$ matrix.[6]

If a sector in the resulting second layer appears in the top q stranding links of more than one sector of the previous layer, it consequently has multiple incoming edges and its input loss is the sum of input losses resulting from all incoming stranding channels.[7] We also add the value of total stranding taking place in each sector in a specific round

[5] Due to the assumption of perfect input substitutability in the Ghosh model, any input loss – may it come from primary or intermediate inputs – corresponds directly to an output loss of the same size, as all other inputs remain unchanged. Thus, the fossil sector at the origin of a stranding cascade is the only sector in the network that changes its primary inputs, while all other sectors experience only losses in intermediate inputs according to fixed output allocation coefficients.

[6] If i is the affected sector and j the originating sector, the allocation coefficient is given by element b_{ij} of the $\mathbf{B}^T$ matrix.

[7] This also means that if q was set equal to the total number of sectors of the IO table (i.e. each layer contains all sectors of the economy), the sum of all incoming edges of a particular sector in a certain layer l would correspond exactly to the total stranding that this sector receives in the l^{th} round of the power series and therefore to the respective sector's element in the fossil mining column of the $\hat{\boldsymbol{\kappa}}(\mathbf{B}^l)^T$ matrix. Thus, the network simply depicts sub-processes of the matrix multiplication of the power series. Setting q equal to the total number of sectors means that all possible stranding channels originating in the fossil sector (i.e. all sub-processes of the matrix multiplication leading to the fossil column of the transposed power series matrices) are considered. By defining the parameter q for filtering the top direct stranding linkages of each sector in each layer, we simply extract the most pronounced stranding channels.

(corresponding to the sum of incoming edges for the case in which q is set equal to the total number of sectors) to the node labels. This makes it possible to compare the size of the displayed (dominant) stranding links to the sum of all possible links.

This procedure can be repeated for an arbitrary number of layers, each one corresponding to a round of the power series. However, the size of effects diminishes with each round. The values of the power series matrices typically become insignificant after seven or eight rounds, and – as will be shown later – most of the effect is captured by the first few rounds (Miller and Blair, 2009). In our representation of the networks, we will focus on the first few rounds and set q sufficiently low to isolate the most important stranding channels and ensure readability of the results. We will also exclude self-loops (i.e. direct stranding from a sector to itself) in order to better investigate inter-industry propagation of effects.

Our second type of network, the exposure network, aims at capturing the main sources and channels that cause certain sectors to be particularly exposed to fossil stranding. Here we again make use of the power series, but construct the network from a different starting point and employ a different selection approach. We first place the sectors of a country that are most exposed to fossil stranding (according to the **S** matrix) at the bottom of the network. For each of those sectors, we then identify the r international fossil sectors they are most exposed to directly (i.e. in the first round of stranding), place them on top of the network and connect them with edge weights corresponding to the direct stranding effect. In the next step, we identify the r most important two-step fossil exposure channels (i.e. indirect incoming stranding linkages originating in a fossil sector with one intermediate step), again add the originating fossil sectors to the top layer and the intermediate sectors to an intermediate layer. Similar to the cascade networks, this procedure could theoretically be repeated for stranding channels of any length. However, we in turn limit our analysis to the first few steps, as the most important transmission channels can be expected within the first few rounds of stranding. This approach allows us to capture the most dominant network origins and transmission channels that create transition risks in vulnerable sectors by means of relatively simple and clear-cut network graphs.

2.3. Data

Our main source of data is the World Input–Output Database (WIOD) (Timmer et al., 2015),[8] which has been used in the past for a variety of research purposes (see Voigt et al., 2014; Marin and Vona, 2019; Klimek et al., 2019; Chen et al., 2019 among others). WIOD is a multi-regional input–output database comprising 43 countries plus a Rest of the World (ROW) region.[9] Most of the countries in the sample have high per capita income, but the dataset also includes several relevant emerging economies (Table 2 lists the whole sample). The sample of non-ROW countries in WIOD allows us to have disaggregated coverage for around 48.3% of oil production; 61.1% of gas production; 89.8% of coal production; and 69.0% of extraction-based CO2 emissions.[10]

The 56 productive sectors present in WIOD are classified using NACE level 2 categories (Eurostat, 2008). Table A.1 in the Appendix lists all sectors included in the analysis. We create new sector codes to make our results easier to understand. The first three upper-case letters of each sector code reflect the NACE level 1 category (e.g. MAN for manufacturing), while the following three lower-case letters reflect the NACE level 2 category (e.g. MANche for manufactured chemical products). When discussing a NACE level 1 sector, or in the case of NACE level 1 sectors for which no further disaggregation is available, we use a + sign at the end of the code, to signify that several sub-activities are included there (e.g. MAN+ is the equivalent of the entire NACE C level 1 sector). The most important sector for our analysis is denominated MINfos, as it records the activities of mining and extraction of fossil fuels, themselves a part of the larger mining sector.

Table 2
WIOD regions.

Income group	Country
High-income	Australia (AUS); Austria (AUT); Belgium (BEL), Canada (CAN), Switzerland (CHE), Cyprus (CYP), Czechia (CZE), Germany (DEU), Denmark (DNK), Spain (ESP), Estonia (EST), Finland (FIN), France (FRA), Great Britain (GBR), Greece (GRC), Croatia (HRV), Hungary (HUN), Ireland (IRL), Italy (ITA), Japan (JPN), South Korea (KOR), Lithuania (LTU), Luxembourg (LUX), Latvia (LVA), Malta (MLT), Netherlands (NLD), Norway (NOR), Poland (POL), Portugal (PRT), Slovakia (SVK), Slovenia (SVN), Sweden (SWE), Taiwan (TWN), United States of America (USA)
Upper-middle	Bulgaria (BGR), Brazil (BRA), China (CHN), Mexico (MEX), Romania (ROU), Russia (RUS), Turkey (TUR)
Lower-middle	Indonesia (IDN), India (IND)

WIOD offers values for the mining sector as a whole (NACE sector B). This is where fossil fuels are extracted, hence at the core of our analysis. However, other materials are also included in the B sector, such as metal ores, stone, sand, clay and numerous other minerals. Hence, using the whole B sector as the core of our analysis will not accurately represent a supply shock in fossil fuels, and thus bias the results. A more detailed disaggregation of the mining sector can be found in the OECD Inter-Country Input–Output (ICIO) database (OECD, 2018). ICIO covers 66 countries (plus a Rest of the World region) and 36 sectors.[11] Even though its overall sectoral resolution is coarser compared to WIOD, the mining sector is disaggregated into three sub-sectors, namely “Mining and extraction of energy producing products” (NACE sectors B05 & B06), “Mining and quarrying of non-energy producing products” (NACE sectors B07 & B08) and “Mining support service activities” (NACE sector B09). Sectors B05 (“Mining of coal and lignite”) and B06 (“Extraction of crude petroleum and natural gas”) contained in the first ICIO mining sub-sector represent the core activities of the fossil extraction industry. Mining support services (specialised support provided to the extraction industry on a fee or contract basis, such as exploration services) are largely part of the fossil complex as well, but they do not directly produce fossil fuels.

We employ this database to split the mining sector in WIOD into three sub-sectors and therefore isolate the fossil extraction industry as our sector of interest.[12] First, we aggregate regions in the 2014 ICIO table to match WIOD regional disaggregation. From this table, we compute (element-wise) ratios to split every mining element in WIOD according to the relative size of the three corresponding sub-sector elements in ICIO.[13] Final demand is disaggregated as a column vector and

[8] A few other MRIO datasets exist, such as EORA (Lenzen, 2011) or EXIOBASE (Stadler et al., 2018) However, to the best of our knowledge, WIOD is the only one offering sector-specific values for physical capital stocks, a necessary component of our analysis. The WIOD database is available at http://www.wiod.org.

[9] One small adjustment was made to the WIOD capital stock dataset prior to the analysis: A negative capital stock value for the Portuguese MANrep sector, likely the result of a negative price deflator, was set to a positive value of the same absolute magnitude.

[10] These values are calculated using BP (2020) for oil, gas and coal production; and SEI et al. (2020) for extraction-based CO2 emissions.

[11] The ICIO database lacks sectoral capital stock data. For this reason, despite its more granular mining classification, it cannot be used as the main data source in our analysis.

[12] The approach we take here is similar to the one used in building the Global Trade Analysis Project (GTAP) database, where the agricultural sectors of some countries' national I–O tables are further disaggregated using more detailed agricultural I–O data from other sources (McDougall, 2009).

[13] Certain sectors have a more granular representation in WIOD than in ICIO. For instance, ICIO has an aggregate sector for agriculture, forestry and

value added (plus taxes less subsidies and transport margins) as a row vector. Second, the resulting WIOD table with a disaggregated mining sector is balanced using a two-stage RAS (TRAS) procedure (Gilchrist and St. Louis, 1999, 2004).[14] This method allows us to ensure consistency between the new mining sub-sectors and the original aggregate WIOD mining sector, while keeping the original WIOD values for all cells unaffected by the mining disaggregation.[15] The result of implementing the TRAS algorithm is a revised WIOD table with three new mining sub-sectors and all other elements identical to the original table.[16] Finally, we split the capital stock of each country's mining sector using the ratios obtained from ICIO total output data. This is made necessary by the unavailability of capital stock data at the sub-sectoral level.

The procedure of splitting and rebalancing an input–output database involves making limiting assumptions and risks altering the underlying data. However, the potential benefits of disaggregating heterogeneous sectors for the accuracy of input–output multipliers – even if based on incomplete information – outweigh the risks, as emphasised by Lenzen (2011). For our specific research purposes, we believe that disaggregating the mining sector to isolate the stranding effects of the fossil fuel industry adds significant value to our analysis while providing plausible estimates.

3. Global fossil stranding

We first analyse the results aggregating $\mathbf{S}$ to obtain a new matrix $\mathbf{S_W}$ showing the stranding interlinkages among global productive sectors. The fossil stranding multipliers of the $\mathbf{S_W}$ matrix provide an estimate of the exposure of capital stock to the risk of remaining unutilised due to a marginal shock in the global fossil mining sector (MINfos). While limited by definition by the lack of regional disaggregation, this analysis is useful to introduce some general implications of fossil stranding. We will relax this limitation in Section 4.

We start by noticing that, among all global productive sectors, the fossil fuel sector is the productive sector with the strongest external stranding potential. Table A.2 in the Appendix ranks sectors according to: (i) their total stranding multiplier; (ii) their external stranding multiplier; (iii) their total stranding exposure; and (iv) their external exposure to stranding from other sectors. In the first column, fossil mining (MINfos) ranks sixth with a total stranding multiplier of 4.636. This means that a marginal reduction in primary inputs of \$1 in the global fossil sector puts \$4.636 of capital at risk of being stranded in the whole economic system. However, most of the stranding risk originating in a sector concerns the sector itself. If we abstract from this internal stranding, the fossil sector appears as the sector capable of creating the largest stranding effect on the rest of the economic system, with an external multiplier of 2.399. It is followed by the waste sector (WATwst) and financial services (FINser). The two final columns give interesting estimates of the total and external exposure of a sector to a scenario with a marginal shock taking place in all sectors (e.g. a generalised drop in economic activity). Due to their high capital intensity and their large use of intermediate inputs, the real estate (RES+) and public administration (PUB+) sectors are by far the most exposed to such a scenario.

Fig. 3 focuses on the stranding cascade originating in the global fossil sector.[17] The fossil mining sector is at the top of the pyramid by choice. The numerical value inside the fossil mining node represents the stranding strength of the initial marginal shock we assume: \$2.099 worth of capital become immediately stranded in the fossil sector due to the \$1 shock in its primary inputs. We then identify the sectors most affected by the lack of intermediate fossil inputs[18] and place them in the first layer. The numerical value attached to the network links represents the strength of that specific stranding relation, while the values inside the nodes reflect the value of the total stranding taking place in the sector in a specific round. The most affected sectors in the first round are the power (PWR+),[19] coke and refined petroleum products (MANref) and basic metals (MANmet) sector. This is unsurprising, as the power and refinery industries require fossil fuels as direct inputs in their production, while the metal industry uses fossil fuels to generate heat (e.g. in blast furnaces). The second layer of the network is composed of the sectors most affected by the stranding taking place in the first-layer sectors. The most relevant stranding links here include the ones connecting the refinery sector with the land transport services sector (TRAinl), which also includes transport via pipelines, and the public administration sector (PUB+); and the one linking the power sector back to the fossil mining sector. The stranding in basic metals cascades down to industries using metallic products, but its strength is less pronounced. Finally, the third layer is composed of the sectors most affected by the stranding originating from the second-layer sectors. Several more downstream sectors appear here. The strength of the single stranding links are lower than in upper layers (the strongest being the one connecting power to real estate services (RES+)) but, due to the multiple active stranding links, the overall stranding in these rounds is still relevant, especially in the power (0.056) and real estate (0.055) sector.

Fig. 4 shows more aggregate results where all stranding impacts coming from different sectors within a certain round have been summed up. We distinguish first-, second- and third-round effects, and aggregate all remaining rounds in the 'Further rounds' category. The overall length of the bar corresponds to the fossil stranding multiplier present in matrix $\mathbf{S_W}$. We report the results for the top 10 sectors by their overall fossil stranding multiplier. We exclude the initial shock impact in the fossil industry, equal to 2.099 and much larger than the stranding impacts on other sectors. For power (PWR+) and refining (MANref), the two most affected sectors, first-round effects are the most relevant. For the following sectors – real estate (RES+), public administration (PUB+), inland transport (TRAinl) and chemicals (MANche) – the opposite seems to be the case. The second-, third- and further-round effects are much larger than first-round effects and strong enough to

fishing, while WIOD has three separates subsectors (A01 to A03). In these cases, we use the mining ratios of the corresponding parent sector in ICIO to disaggregate their transactions with mining industries, and apply this to all corresponding WIOD subsectors. For the NACE sector U ("Activities of extraterritorial organisations and bodies"), which is not included in ICIO, we split transactions with the B sector (if existing) into three equal parts.

[14] In a RAS procedure, a technical matrix (A) is pre-multiplied and post-multiplied by diagonal matrices R and S to derive a new technical matrix with specified row and column sums. TRAS is an extension of this procedure, additionally allowing for constraints on arbitrary subsets of matrix cells.

[15] More specifically, every non-mining cell is constrained by its original value and every aggregate of the three mining sub-sectors (i.e. a block of 3×1 cells in mining rows, 1×3 cells in mining columns, or 3×3 cells in mining intra-industry trade) is constrained by the original value of the B sector.

[16] Two small preparatory adjustments are made to ease the convergence of the algorithm. First, zeros resulting from the mining disaggregation process are replaced by small positive values. Second, several negative values that are naturally contained in the WIOD final demand and value added vectors are masked during the balancing procedure. Once these adjustments are complete, the TRAS algorithm proceeds with two steps in each iteration: (i) a rescaling of rows and columns in a RAS step; and (ii) a rescaling of the known cells and cell aggregates in a TRAS step. The algorithm stops when all row, column and cell rescaling factors converge to unity (given a certain tolerance value).

[17] Edge values smaller than 0.001 are not displayed to improve the readability of the graph.

[18] The choice of q is arbitrary. We choose $q = 3$ to create a readable network with enough depth.

[19] The power sector includes the production and distribution of electricity, natural gas, steam and hot water (for heating, power and other purposes) and air conditioning. We use the terms "power sector" and "electricity and gas sector" interchangeably in this article.

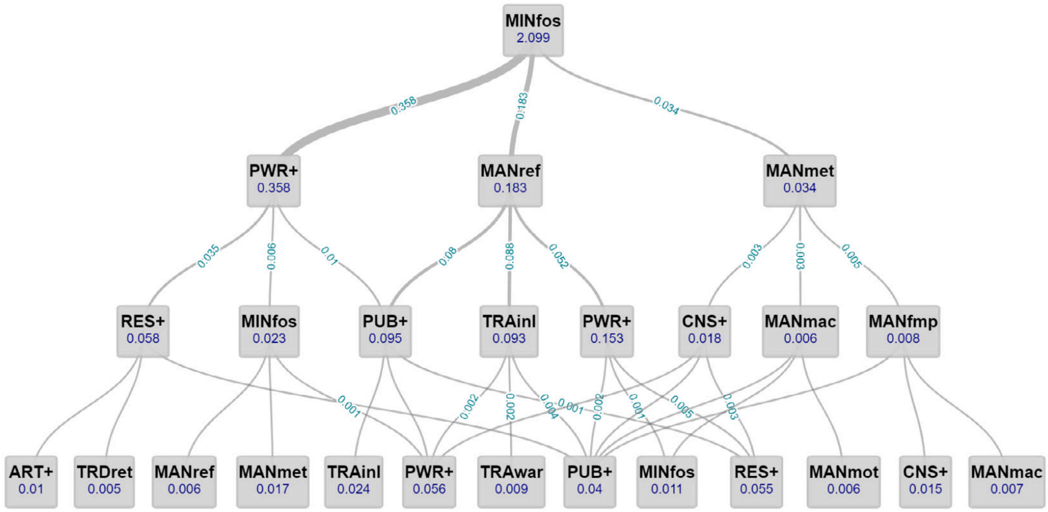

Fig. 3. Stranding cascade from the global fossil mining sector ($q = 3$). Edge labels represent the strength of the stranding relation from the upper node to the lower node. Values inside the nodes reflect the value of the total stranding taking place in the sector in a specific round (i.e. considering all possible incoming links).

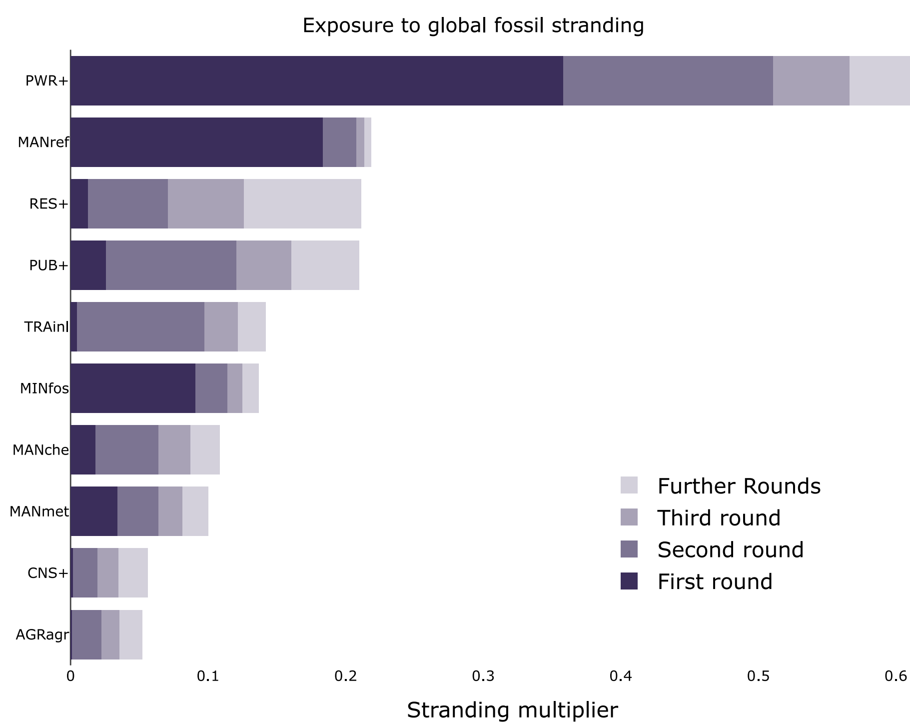

Fig. 4. Top 10 global sectors by their exposure to fossil stranding, disaggregated into direct (first round) and subsequent indirect rounds of effects.

move their fossil stranding multiplier above the one of basic metals (MANmet), which has the fourth-largest direct stranding effect as seen in Fig. 3. These results support our initial hypothesis that downstream sectors can be significantly exposed to stranding risks, possibly to a comparable extent as upstream sectors that rely more directly on fossil fuels.

The strong indirect exposure of these downstream service sectors depicted in Figs. 3 and 4 can be explained both by their high capital intensity and the (direct and indirect) fossil intensity of the intermediate inputs they use. The real estate sector still heavily relies on fossil energy provided by the power and refining industries for the supply of heating and electricity to buildings[20] (see Fig. A.1 in the appendix for an exposure network of the global real estate sector). It also represents a major user of construction services, which in turn strongly depend

[20] Note that energy use of buildings typically does not represent an intermediate use item of the real estate sector itself, but a use item of the commercial (intermediate) or residential (final) users of the buildings (i.e. real estate services only include “cold rents”). The real estate sector still records significant intermediate consumption of power and refined fuels, due to the operation of “common areas” (e.g. hallways, elevators) not directly rented out to individual tenants and statistical difficulties in disentangling pure “cold” rental services from energy-inclusive rents.

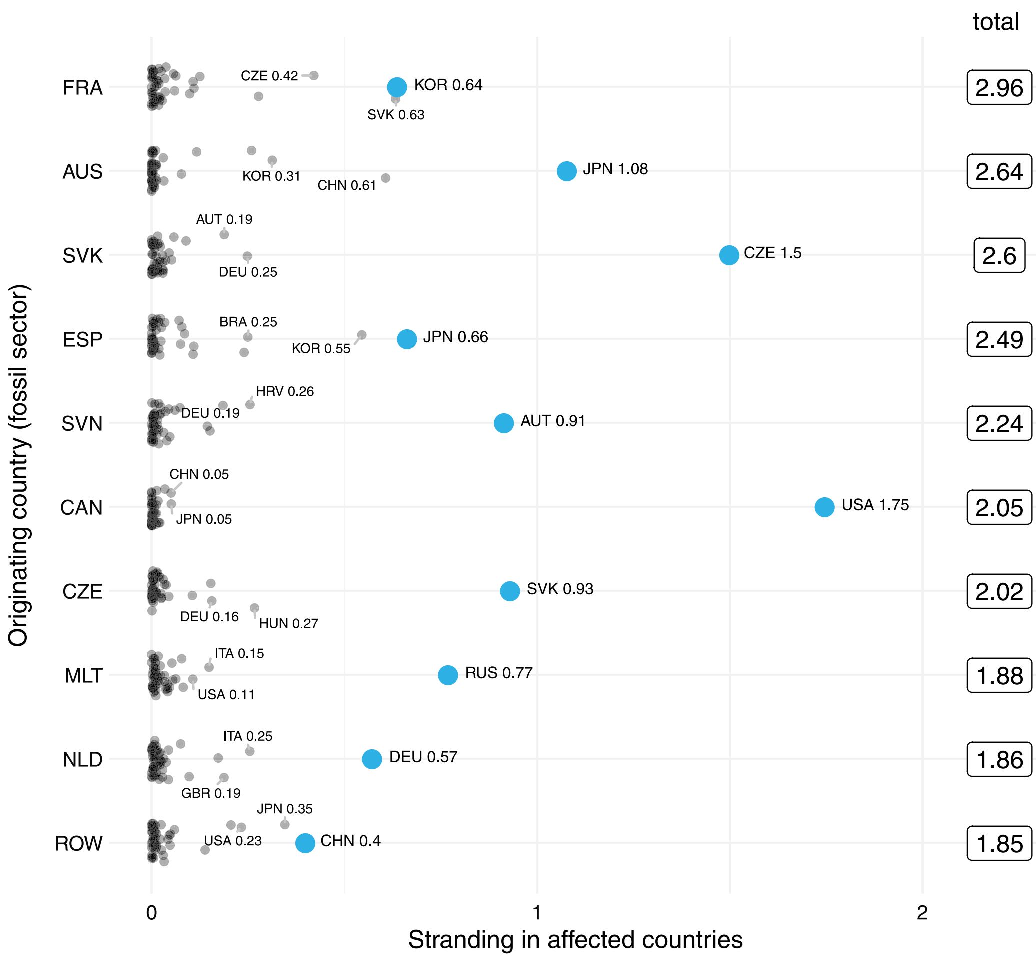

Fig. 5. Top 10 countries for external fossil stranding multipliers. Framed values on the right represent the external multiplier of the given country (stranding effect on all other countries). Dots represent the stranding effect on individual countries, with the three highest values labelled and the top value marked in blue.

on fossil inputs. Together with the high capital intensity of real estate activities, this generates significant indirect stranding exposure. The high exposure of public administration might be more surprising, but can be explained by two driving factors (Fig. A.2). First, the public sector is a major owner of buildings and infrastructure directly and indirectly requiring fossil energy and intermediate inputs. Second, this sector includes military and defence activities, which also employ considerable amounts of fossil fuels (military activities rank very high in terms of greenhouse gas emissions; see for instance Crawford, 2019). The land transport sector contains rail- and road-based passenger and freight transport services (both public and private) as well as transport via pipelines. Consequently, it is strongly hit by second-round effects coming from the refining industry, due to both the use of refined fuels in combustion engines and their transportation via pipelines (Fig. A.3).

4. Cross-country fossil stranding

We now relax our previous assumption of globally integrated sectors to explore the more granular results offered by the full **S** matrix. Before doing so, it is worth reminding that the shock we investigate – a marginal reduction of primary inputs employed in the domestic production of fossil fuels – is applied equally to all countries, irrespective of their absolute amounts of fossil fuel extraction. Hence, the resulting stranding results do not depend on the relevance of the country as a producer or exporter of fossil fuel, but rather on: (i) how concentrated are monetary outflows from the fossil industry towards specific sectors; and (ii) how capital intensive are the sectors receiving fossil products. A marginal shock in a country where the entire amount of fossil products flows to a single sector with high capital intensity will cause large capital stranding effects, even if fossil fuel extraction levels are very low.

We start by discussing countries' total fossil stranding potential. The left column of Table A.3 in the Appendix ranks countries by their overall global stranding potential. The numerical values listed indicate the monetary value of the physical capital at risk of remaining idle in the whole economic system due to a fossil shock in the respective country. The results are strongly shaped by the capital intensity of domestic fossil sectors, where the initial marginal shock takes place. Indeed, the countries in the top 3 of the ranking (Slovakia, Brazil and Australia) are also in the top 3 of countries ranked by the capital intensity of their fossil sectors. The explanation for having Luxembourg in fourth place is different. The Luxembourg fossil sector is not particularly capital intensive, but almost 96% of its (very small) fossil mining output goes to its capital-intensive electricity and gas sector. A similar explanation applies to South Korea, in fifth position.

To abstract from domestic stranding, we look at the ranking of countries according to the stranding they create externally to other countries. Fig. 5 shows the top 10 countries by their external stranding multiplier, with a disaggregation of the most affected countries.[21] As with total stranding rankings, low levels of fossil extraction do not contribute to shaping the results. France, a marginal producer of fossil fuels, is at the top of the ranking, mainly due to the very high proportion of production being exported (96%) and the high capital intensity

[21] The entire ranking is available in the middle column of Table A.3.

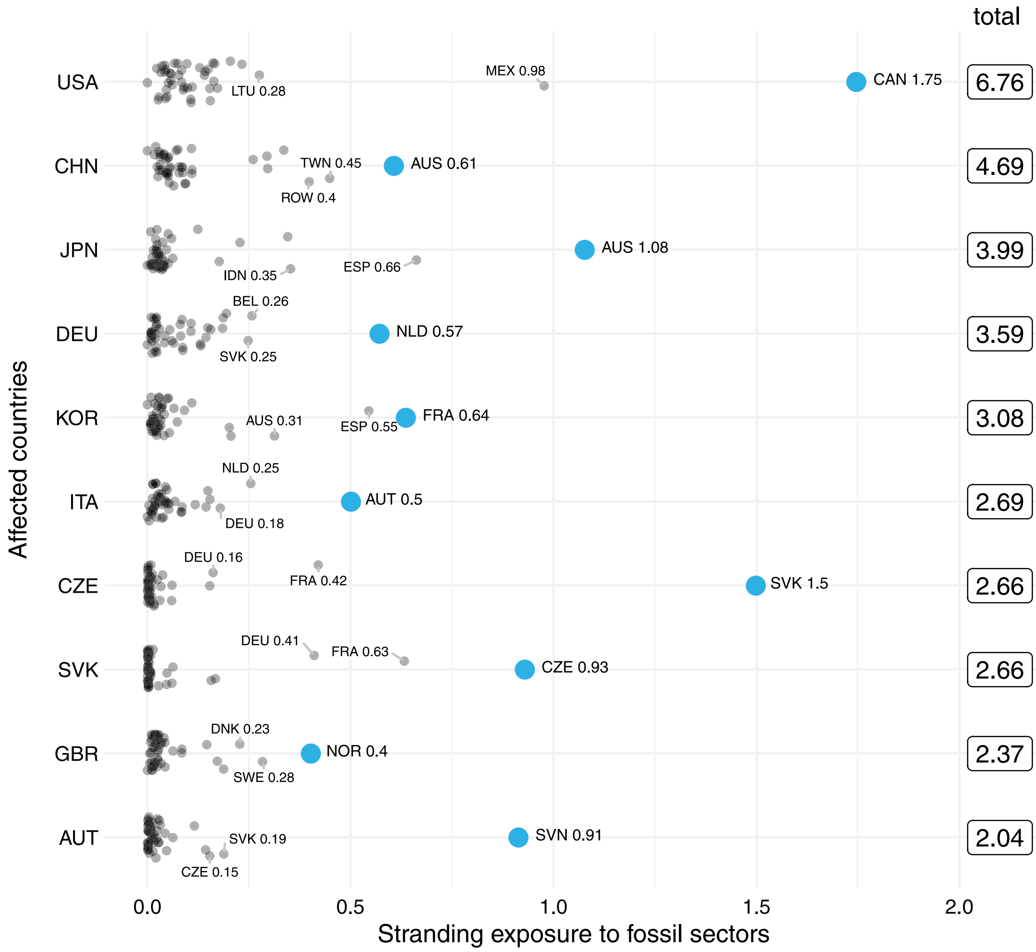

Fig. 6. Top 10 countries for external exposure to fossil stranding risk. Framed values on the right represent the total external exposure of the given country (stranding effect in case of a unitary supply shock in the fossil industries of all other countries). Dots represent the stranding exposure to individual countries' fossil industries, with the three highest values labelled and the top value marked in blue.

of its major importing sectors (especially Slovakian power and refining sectors). Australia is in second place, mainly due to the strong stranding effect created on the Japanese power sector and to a lesser extent the power sectors of China, South Korea and Taiwan. Slovakia ranks third, predominantly due to its high stranding effects on the Czech economy, which also creates relevant stranding links back to Slovakia (in seventh place). These results suggest the permanence of a strong integration between the two productive systems after the separation of the two countries in 1993.

It should also be noted how the USA and China – the two largest fossil fuel producers in our sample – are at the bottom of the external stranding ranking. While this might seem counter-intuitive, this is easily explained by two facts. First, the large majority of their fossil fuel production (92.5% for USA and 99.5% for China) is consumed internally; therefore most of the stranding effects are felt internally. Indeed, both countries rank much higher in the total stranding ranking that includes domestic stranding (15th position for USA; 22nd for China). Second, they export fossil fuels to a large number of countries (i.e. their fossil outflows have a lower concentration) whose sectors have relatively lower capital intensity.

Finally, Fig. 6 ranks the top 10 countries according to their exposure to fossil stranding coming from abroad.[22] The total exposure values listed represent the monetary value becoming stranded in the country in the scenario of a generalised drop of external fossil fuel extraction (i.e. a marginal shock is assumed to take place in all the countries of the sample, except for the country for which we analyse exposure). We are also able to disaggregate this exposure to stranding by originating country. The USA is by far the most exposed country ($6.76 of capital are exposed to stranding risk in the case of a generalised production decline of $1 in all foreign fossil sectors), with Canada (1.75) and Mexico (0.98) being the most relevant origins of these stranding risks (followed by Lithuania, ROW and Finland, with much lower values). China is the second most exposed country (with a coefficient of 4.69). In the Chinese case, potential origins of stranding risk are more diversified than for the US. Australian (0.61) and Taiwanese (0.45) fossil sectors are the ones with the highest stranding effect on China, closely followed by ROW (0.40), South Korea (0.34), Russia (0.30), Brazil (0.29) and others. Japan is in third place of the ranking with a total exposure coefficient of 3.99, originating predominantly in Australia (1.08) and Spain (0.66).

5. Fossil stranding exposure

We now move to analysing more in depth how countries are exposed to fossil stranding links, looking at the network origins and transmission channels. We do so by constructing exposure networks representing the most relevant one-step (i.e. direct), two-step and three-step (i.e. indirect with respectively one and two intermediate steps) stranding links affecting the most overall exposed sectors of the selected country. We focus on three countries: USA, China and Germany. These are among the countries most exposed to supply-side external stranding

[22] See the right column of Table A.3 for a full ranking

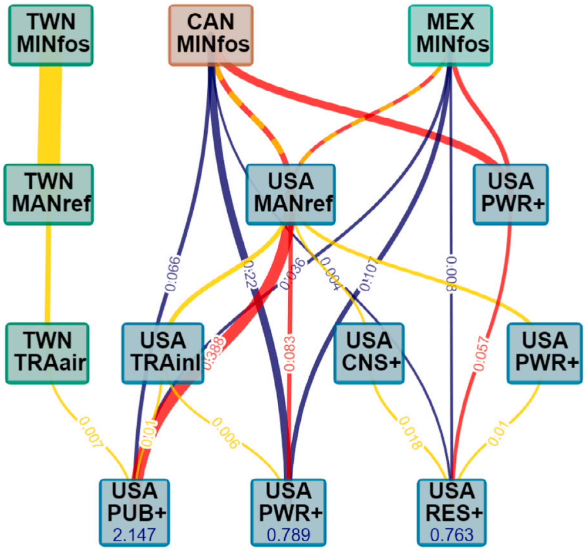

Fig. 7. Main fossil exposure links for the USA ($r = 2$). Direct (one-step) links are blue, two-step links red and three-step links yellow. Edge values represent the stranding effect of a cascade on the exposed sectors on the bottom. Values inside the bottom nodes reflect their total external exposure (to all foreign fossil industries).

risk,[23] as shown in Table A.3 and Fig. 6. USA and China are also the largest economies in the world and the largest producers and consumers of fossil fuels in our country sample. We exclude internal stranding exposure (to the domestic fossil sector) from the analysis in order to focus on cross-boundary (external) exposure linkages.

Fig. 7 shows the exposure network for the USA. The most exposed US sectors, according to the marginal stranding multipliers found in matrix **S**, are public administration (PUB+), electricity and gas (PWR+), and real estate (RES+). We place them at the bottom of the network and add their total external exposure values to the node labels. We then look for their strongest incoming one-step, two-step and three-step fossil stranding links to understand where their exposure originates and how it reaches them through the production network, as discussed in Section 2.2. The choice of the number of steps is arbitrary, but most of the dominant stranding cascades can be expected to take place within the first few steps. By setting $r = 2$ we select the two most important stranding channels for each of the three cascade lengths.

As already observed in Fig. 6, US sectors appear heavily exposed to the Canadian and Mexican fossil (MINfos) sectors. Significant direct stranding links exist between them and all of the US sectors at the bottom of the network, with the one linking Canada's fossil sector and the US power (PWR+) industry being the strongest. Indeed, shocks originating in Canada, the main fossil exporter in our sample, affect the US economy more than the Canadian economy itself. Several important two-step stranding links also exist, with the most relevant connecting the Canadian and Mexican fossil sector to the US refining and coke industry (MANref), and then from there to US public administration (PUB+) and, to a lesser extent, the US power sector. Three-step stranding chains follow similar channels, with USA refining affecting the domestic land transport (TRAinl), construction (CNS+) and power industries, which then in turn affect the sectors at the bottom. In addition, we spot a three-step stranding cascade originating in the Taiwan fossil industry, passing through the Taiwanese refining and air transport (TRAair) industry, and finally affecting the USA public administration sector. This cascade draws its strength primarily from the substantial linkage between Taiwan's fossil and refining industries,

[23] We prefer Germany to Japan, despite the latter exhibits a higher exposure multiplier than the former, to have a more diverse regional representation.

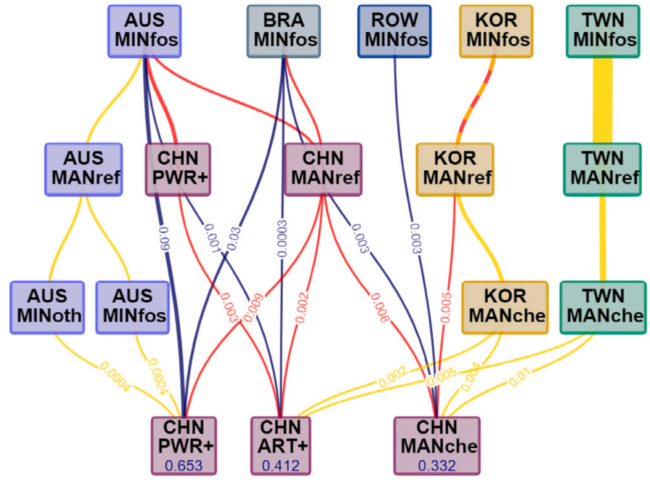

Fig. 8. Main fossil exposure links for China ($r = 2$).

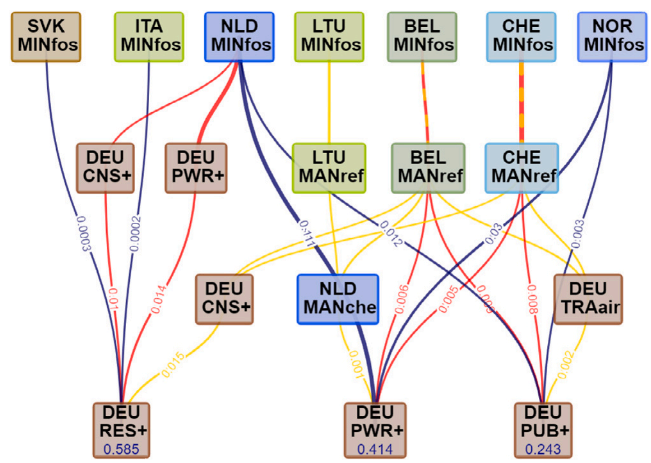

Fig. 9. Main fossil exposure links for Germany ($r = 2$).

arising from the fact that almost all of the Taiwanese fossil extraction is used by the domestic refinery industry.[24] This strong impulse then trickles through to the US public administration sector via Taiwan's air transport industry, which serves as a major trans-pacific cargo service provider and is used by the US public administration sector to import manufactured goods. However, due to the very limited production volume of the Taiwanese fossil industry, this cascade is of little practical relevance. Rather, it again shows that sectors with a concentrated use structure typically have high marginal stranding potential.

Fig. 8 shows the results for China. The Chinese sectors with the highest overall exposure multipliers are power (PWR+), the arts, entertainment and recreation sector (ART+), and the chemical industry (MANche). We find that the most relevant originating fossil sectors are the Australian, Brazilian and ROW ones for what concerns direct stranding links, with the one going from Australia to the Chinese power sector being the strongest. Two-step cascades also originate from Australia and Brazil, passing through the Chinese power and refining sectors, with an additional cascade originating in the Korean fossil sector and affecting the Chinese chemical sectors via Korea's refining industry.

[24] This link is further exacerbated by a negative inventory change of the TWN MINfos sector in 2014, which effectively reduces its total output of the same year and consequently increases the sector's output allocation coefficients.

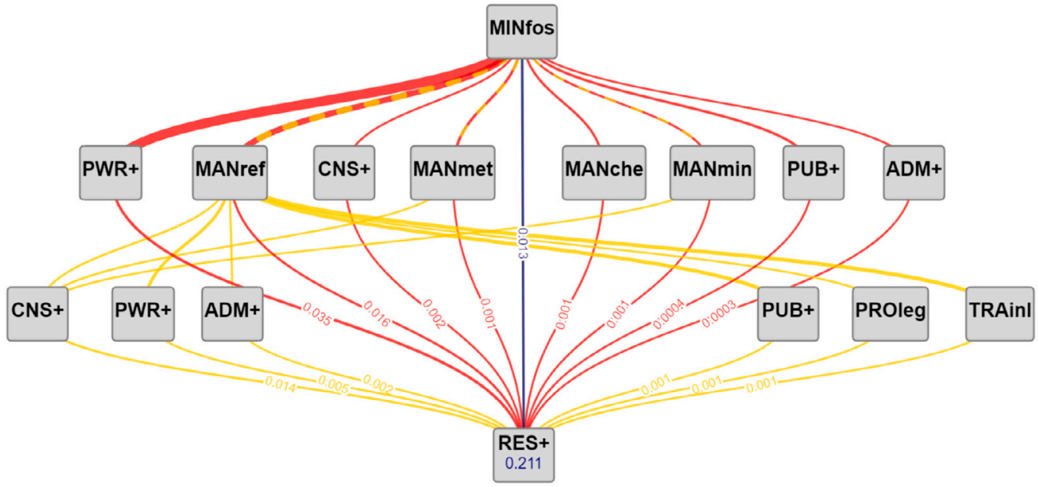

Fig. A.1. Main fossil exposure links for the global real estate sector ($r = 8$). Direct (one-step) links are blue, two-step links red and three-step links yellow. Edge values represent the stranding effect of a cascade on the exposed sectors on the bottom. Values inside the bottom nodes reflect their total exposure to fossil stranding.

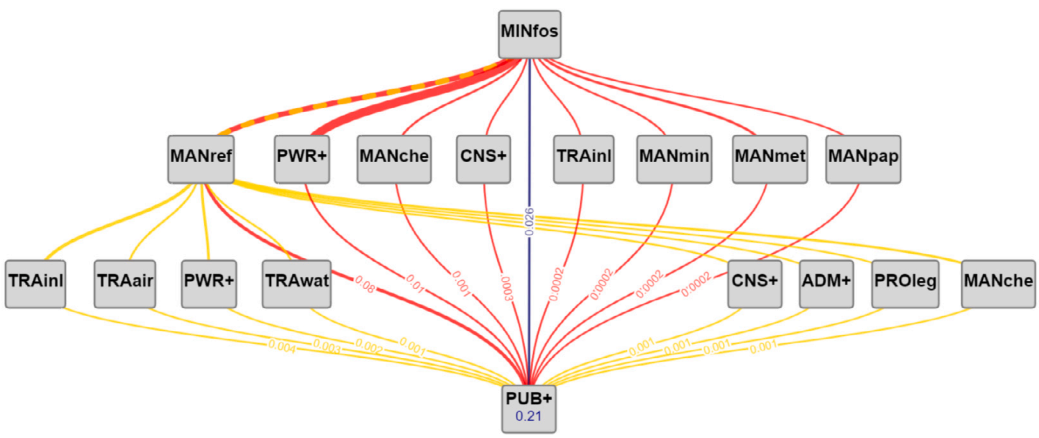

Fig. A.2. Main fossil exposure links for the global public administration sector ($r = 8$).

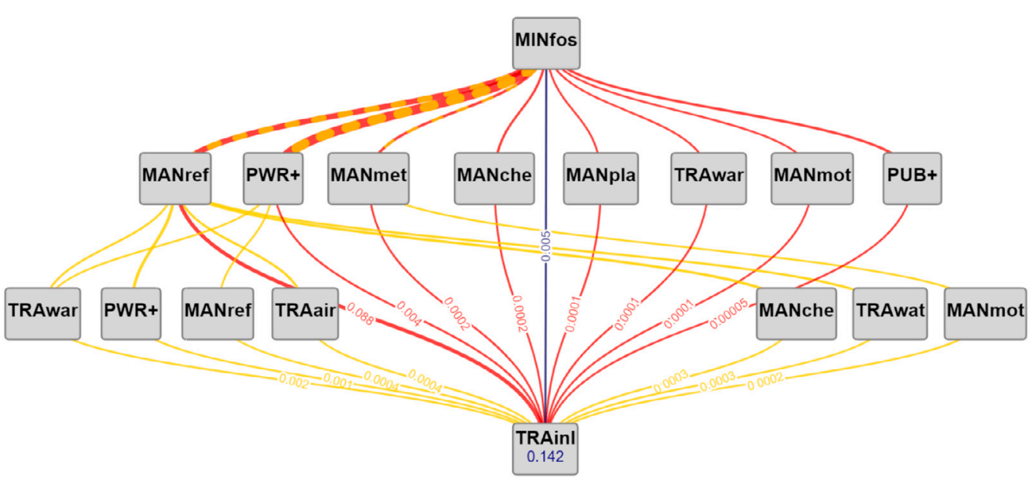

Fig. A.3. Main fossil exposure links for the global land transport sector ($r = 8$).

Three-step cascades identify three alternative transmission channels: (i) a cascade mainly internal to Australia (from fossil mining to refining and back to the fossil/non-fossil mining industry) and affecting China's power sector; (ii) a variation on the Korean cascade passing through Korean chemicals; and (iii) a cascade originating in Taiwan, passing through Taiwan's refining and chemical industries, and landing on both China's arts, entertainment and recreation and chemical sectors.

We notice how the stranding links of the networks explain only a minor proportion of the overall external stranding in the bottom sectors (value reported inside the node). This is due to the exposure of China to a multiplicity of countries, although with lower singular effects, as

Table A.1
NACE level 2 sectors[a].

NACE	Code	Sector description
A	AGR+	Agriculture, forestry and fishing
A01	AGRagr	Crop and animal production, hunting and related service activities
A02	AGRfor	Forestry and logging
A03	AGRfis	Fishing and aquaculture
B	MIN+	Mining and quarrying
B05–06	MINfos	Mining and extraction of energy producing products
B07–08	MINoth	Mining and quarrying of non-energy producing products
B09	MINsup	Mining support service activities
C	MAN+	Manufacturing
C10–12	MANfoo	Food, beverages and tobacco products
C13–15	MANtex	Textiles, wearing apparel, leather and related products
C16	MANwoo	Wood and products of wood and cork, except furniture
C17	MANpap	Paper and paper products
C18	MANpri	Printing and reproduction of recorded media
C19	MANref	Coke and refined petroleum products
C20	MANche	Chemicals and chemical products
C21	MANpha	Basic pharmaceutical products and pharmaceutical preparations
C22	MANpla	Rubber and plastic products
C23	MANmin	Other non-metallic mineral products
C24	MANmet	Basic metals
C25	MANfmp	Fabricated metal products, except machinery and equipment
C26	MANcom	Computer, electronic and optical products
C27	MANele	Electrical equipment
C28	MANmac	Machinery and equipment n.e.c.
C29	MANmot	Motor vehicles, trailers and semi-trailers
C30	MANtra	Other transport equipment
C31_32	MANfur	Furniture and other manufactured goods
C33	MANrep	Repair and installation services of machinery and equipment
D	PWR+	Electricity, gas, steam and air conditioning
E	WAT+	Water supply; sewerage; waste management and remediation
E36	WATwat	Natural water; water treatment and supply services
E37–39	WATwst	Sewerage services; sewage sludge; waste collection, treatment and disposal services
F	CNS+	Constructions and construction works
G	TRD+	Wholesale and retail trade; repair of motor vehicles and motorcycles
G45	TRDmot	Wholesale and retail trade and repair services of motor vehicles and motorcycles
G46	TRDwho	Wholesale trade, except of motor vehicles and motorcycles
G47	TRDret	Retail trade services, except of motor vehicles and motorcycles
H	TRA+	Transportation and storage
H49	TRAinl	Land transport and transport via pipelines
H50	TRAwat	Water transport
H51	TRAair	Air transport
H52	TRAwar	Warehousing and support activities for transportation
H53	TRApos	Postal and courier activities
I	FD+	Accommodation and food service activities
J	COM+	Information and communication
J58	COMpub	Publishing activities
J59_60	COMvid	Motion picture, video and television production, sound recording, broadcasting
J61	COMtel	Telecommunications
J62_63	COMcom	Computer programming, consultancy; Information service activities
K	FIN+	Financial and insurance activities
K64	FINser	Financial services, except insurance and pension funding
K65	FINins	Insurance, reinsurance and pension funding services, except compulsory social security
K66	FINaux	Activities auxiliary to financial services and insurance services
L	RES+	Real estate activities
M	PRO+	Professional, scientific and technical activities
M69_70	PROleg	Legal and accounting services; Activities of head offices; management consultancy activities
M71	PROeng	Architectural and engineering activities; technical testing and analysis
M72	PROsci	Scientific research and development
M73	PROadv	Advertising and market research
M74_75	PROoth	Other professional, scientific and technical activities; Veterinary activities
N	ADM+	Administrative and support service activities
O	PUB+	Public administration and defence; compulsory social security
P	EDU+	Education
Q	HEA+	Human health and social work activities
R_S	ART+	Arts, entertainment and recreation
U	HOU+	Activities of households as employers

[a]See Eurostat (2008) for a more detailed description of NACE codes.

already shown by Fig. 6. This is in contrast to the US situation, which is instead mainly exposed to two very strong stranding links.

Australia is also a major fossil exporter, and towards the top of countries ranked according to their external stranding potential (see Table A.3). It is worth mentioning that, while China is indeed one of the most affected countries by a marginal shock originating in the Australian fossil mining sector, the Japanese economy is even more exposed to it than China.

Finally, Fig. 9 represents the exposure of the German economy. The high number of European fossil fuel sectors from which stranding originates illustrates well the integration of Germany into European energy value chains. It is also indicative of the strong integration

Table A.2
Top 15 global sectors by stranding and exposure.

	Total stranding	External stranding	Total exposure	External exposure
1	RES+ (9.971)	MINfos (2.399)	RES+ (22.512)	RES+ (12.972)
2	WATwat (6.922)	WATwst (2.349)	PUB+ (11.768)	PUB+ (8.603)
3	COMvid (5.701)	FINser (2.309)	PWR+ (7.493)	PWR+ (4.134)
4	PWR+ (5.214)	ADM+ (2.209)	WATwat (5.939)	TRAinl (2.674)
5	WATwst (4.922)	TRApos (2.122)	COMvid (5.602)	CNS+ (2.592)
6	MINfos (4.636)	PROleg (2.045)	ART+ (4.729)	ART+ (2.505)
7	MINsup (4.355)	MINoth (2.033)	TRAinl (4.573)	MANfoo (1.888)
8	MINoth (4.168)	MANpri (2.01)	MINfos (3.979)	HEA+ (1.798)
9	TRAwar (3.91)	PROadv (1.942)	COMtel (3.58)	MINfos (1.743)
10	PUB+ (3.389)	MANref (1.922)	AGRagr (3.29)	MANmet (1.686)
11	ADM+ (3.311)	PWR+ (1.855)	TRAwar (3.287)	AGRagr (1.684)
12	AGRfor (3.25)	TRAwar (1.825)	WATwst (3.15)	MANche (1.639)
13	COMtel (3.237)	MINsup (1.823)	MINoth (3.012)	COMtel (1.543)
14	TRAinl (3.194)	MANpap (1.801)	CNS+ (2.998)	MANmot (1.29)
15	TRApos (3.178)	AGRfor (1.798)	MINsup (2.8)	FD+ (1.257)

of European economies. The most affected sectors in terms of overall stranding multipliers are the real estate (RES+), power (PWR+), and public administration (PUB+) sector. The most relevant one-step stranding links originate in the Dutch fossil sector and affect the power and public administration sectors in Germany. Significant direct links originate also in Norway, Slovakia and Italy. Relevant two-step stranding cascades originate in the Netherlands, Belgium and Switzerland, through the German construction (CNS+) and power sectors, and through the Belgian and Swiss coke and refinery industries. Three-step stranding cascades originate from Lithuania, Belgium and Switzerland; pass through their respective coke and refinery sectors in the first stranding layer; touch the German construction and air transport (TRAair) sectors, and the Dutch chemicals (MANche) sector; before landing on all three bottom sectors.

6. Limitations and future avenues of research

Our analysis is not exempt from limitations. First, it is limited by data availability and granularity. We are not able to disaggregate among specific types of capital stocks (e.g. machinery vs. dwellings), despite they are probably exposed to stranding risks to different extents. We have good coverage of global fossil extraction but we miss disaggregated data for several important fossil producers/exporters (e.g. Saudi Arabia, Venezuela, South Africa). Sectoral capital stocks might not be entirely precise due to the need of balancing the MRIO table (which is done at two stages; once by WIOD researchers, and once by us after splitting the mining sector). The use of industry-by-industry tables, rather than product-by-product, can also give rise to imprecision in our calculations. Second, we rely on a number of limiting assumptions, mostly inherited by the use of input–output methods and the Ghosh supply-driven framework. As a consequence, our results are valid only for marginal shocks and should not be mistaken as an estimate of actual stranding impacts in a low-carbon transition scenario, as the latter would involve price adjustments, substitution of inputs, technological progress and change in preferences. Rather, our analysis offers insights on the interdependent nature of international economic sectors and the importance of fossil fuel extraction for downstream sectors.

We also hope to contribute to opening further research avenues building on the methodology and results presented here. Some of these avenues could be pursued with relatively limited modifications. For instance, replacing capital stock data with sectoral employment values could offer insights on the transition implications on labour, as in Perrier and Quirion (2018) and Bastidas and Mc Isaac (2019). Instead of adopting a supply-side approach focused on fossil sectors, it would be possible to use the Leontief model to study the stranding implications of sectoral demand constraints depending on their carbon intensity. Other research avenues would instead require more work. We highlight two. First, dynamic effects could be included by inserting the MRIO analysis into a macroeconomic modelling framework (e.g. using computable general equilibrium or stock-flow consistent models). Second, the analysis of production networks could be linked to the ongoing study of financial networks to create a multi-layer network analysis capable of offering a more complete perspective on how the macro-financial system would react to a low-carbon transition.

7. Conclusion

The systemic risks of transitioning to a low-carbon society under the current technological conditions are complex and still largely unknown. We contribute to filling this research gap by developing a simple methodology to calculate the monetary value of capital stocks at risk of becoming stranded as a consequence of a marginal loss of primary inputs employed in the fossil sector, taking into consideration the network of economic inter-dependencies. We apply the methodology to a revised version of the WIOD multi-regional database to compute (i) the marginal stranding multipliers of countries' fossil sectors; (ii) the exposure of national economic systems to the risk of capital stranding coming from fossil sectors abroad.

We obtain several interesting results. First, among all productive sectors, fossil industries exhibit the strongest potential to create capital stranding in other sectors. Second, we show that, while some sectors (e.g. energy and manufacturing) are directly exposed to the fossil shock, several other productive activities are mainly affected by indirect effects. Indeed, when taking into account all rounds of stranding, service sectors like real estate and public administration rank amongst the most affected ones by global fossil stranding. This supports the intuition that the whole global productive system would be affected by the decarbonisation process, and not only heavy industry sectors using fossil fuels as direct inputs.

Third, we rank countries according to their external stranding potential, finding France, Australia and Slovakia at the top of the ranking, and the USA and Italy at its bottom. These results can seem surprising but they are explained by the proportion of the exported fossil production of the top countries and the capital intensity of the sectors importing this production. On the contrary, major producers whose production is largely consumed onshore, such as the USA and China, are at the bottom of the external stranding ranking. Our results therefore show the counter-intuitive fact that a country's marginal stranding power does not correlate automatically with its importance in global fossil fuels production. We also show how the capital stocks of the USA, China and Japan are the most exposed to the risk of stranding due to a generalised drop in foreign fossil production. Finally, we zoom on a selection of countries (USA, China and Germany) to provide a more granular understanding of how their productive systems are exposed to direct or indirect stranding risk. In all three countries, the main stranding cascades end in secondary and tertiary sectors, which are mainly hit via indirect network effects.

Despite the limits mentioned above, our analysis still offers meaningful results with important implications for policy-makers. There has

Table A.3
Ranking of countries by stranding and exposure.

	Total stranding	External stranding	External exposure
1	SVK (8.802)	FRA (2.961)	USA (6.762)
2	BRA (7.394)	AUS (2.638)	CHN (4.695)
3	AUS (7.273)	SVK (2.598)	JPN (3.992)
4	LUX (7.055)	ESP (2.494)	DEU (3.586)
5	KOR (6.213)	SVN (2.241)	KOR (3.081)
6	FRA (5.972)	CAN (2.052)	ITA (2.688)
7	CZE (5.847)	CZE (2.015)	CZE (2.66)
8	SVN (5.834)	MLT (1.882)	SVK (2.657)
9	HUN (5.485)	NLD (1.864)	GBR (2.367)
10	CAN (5.43)	DEU (1.814)	AUT (2.037)
11	IND (5.366)	AUT (1.58)	ESP (1.936)
12	EST (5.338)	DNK (1.57)	FRA (1.77)
13	TWN (5.201)	NOR (1.555)	RUS (1.669)
14	DNK (5.079)	BEL (1.551)	HUN (1.423)
15	USA (4.892)	FIN (1.525)	SWE (1.386)
16	PRT (4.871)	RUS (1.515)	TUR (1.205)
17	LVA (4.844)	LVA (1.509)	IND (1.164)
18	ESP (4.644)	SWE (1.489)	BRA (1.069)
19	RUS (4.575)	LTU (1.471)	TWN (1.037)
20	ROU (4.51)	MEX (1.421)	BEL (1.02)
21	CYP (4.47)	IDN (1.36)	FIN (0.969)
22	CHN (4.437)	TWN (1.165)	NLD (0.876)
23	FIN (4.244)	BGR (1.155)	IDN (0.764)
24	TUR (4.178)	KOR (1.144)	ROU (0.663)
25	BGR (4.174)	HUN (1.132)	POL (0.628)
26	AUT (4.117)	EST (1.097)	DNK (0.589)
27	IRL (4.039)	CHE (1.049)	HRV (0.578)
28	MEX (4.007)	POL (0.934)	AUS (0.543)
29	NLD (3.893)	GBR (0.901)	NOR (0.54)
30	MLT (3.855)	GRC (0.899)	CHE (0.46)
31	JPN (3.818)	PRT (0.887)	BGR (0.424)
32	SWE (3.755)	CYP (0.851)	CAN (0.374)
33	GBR (3.697)	LUX (0.774)	PRT (0.328)
34	NOR (3.681)	HRV (0.757)	MEX (0.309)
35	CHE (3.466)	TUR (0.677)	LVA (0.298)
36	IDN (3.452)	BRA (0.647)	SVN (0.19)
37	LTU (3.422)	ROU (0.449)	GRC (0.152)
38	DEU (3.352)	IRL (0.437)	LTU (0.133)
39	ITA (3.345)	IND (0.408)	EST (0.13)
40	HRV (3.026)	JPN (0.371)	IRL (0.118)
41	GRC (2.971)	USA (0.29)	LUX (0.075)
42	BEL (2.893)	ITA (0.224)	CYP (0.048)
43	POL (2.828)	CHN (0.212)	MLT (0.021)

been a strong expansion of research contributions trying to assess the macro-financial implications of a low-carbon transition (Allen et al., 2020; Vermeulen et al., 2018). This is of particular interest to central banks, financial supervisors and other institutions interested in mitigating climate-related financial risks. Including a systemic view on capital stranding through the representation of production networks, as we do for the first time in this article, might contribute to the definition of more sophisticated and comprehensive risk assessment methods.

CRediT authorship contribution statement

Louison Cahen-Fourot: Methodology, Investigation, Writing – original draft, Visualization. **Emanuele Campiglio:** Conceptualization, Methodology, Software, Investigation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Antoine Godin:** Conceptualization, Methodology, Investigation, Writing – original draft, Funding acquisition. **Eric Kemp-Benedict:** Conceptualization, Methodology, Software, Investigation, Writing – original draft, Funding acquisition. **Stefan Trsek:** Methodology, Software, Investigation, Data Curation, Writing – original draft, Writing – review & editing, Visualization.

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Appendix A. Sector codes and descriptions

See Table A.1.

Appendix B. Sectoral global stranding

See Table A.2.

Appendix C. Exposure networks for global service sectors

See Figs. A.1–A.3.

Appendix D. Country stranding multipliers and exposure

See Table A.3.

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