Networks of stranded assets: A case for a balance sheet approach

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Abstract
Moving to a low-carbon economic system will require several industrial sectors to undertake a deep technological transformation of their production processes, leading some of their physical capital assets to become stranded. This might also have a large-scale impact on the assets of the upstream and downstream sectors, producing a 'cascade of asset stranding', which might in turn lead financial assets to lose part of their value. Using French input-output tables as a case study, we investigate the relevance of this scenario by developing a novel measure of 'basic centrality' to identify relevant economic sectors from a biophysical perspective. We find the extractive sector to be at the bottom of an 'inverted pyramid' of interconnections. We then study the resulting network to understand the most significant channels through which a transition away from fossil fuels might propagate to the rest of the system and produce stranded assets. Understanding the financial implications of this cascade suggests the need for a balance sheet approach, both for empirical analysis and for dynamic modelling.

Keywords: Stranded assets; low-carbon transition; networks; input-output analysis; Stock-Flow Consistent models

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1 Introduction

Respecting the 2°C target on the increase in global temperatures will require a large-scale transition to low-carbon forms of capital stock and infrastructure, which is likely to deeply affect (and be affected by) the rest of the macroeconomic and financial system (IPCC 2014). As in other energy transitions and waves of technical innovation in the past, achieving a low-carbon society will require a multidimensional transformation of technologies, markets, infrastructure, markets and behaviors (Perez 2010; Schumpeter 1911).

The process of emergence of a new techno-economic paradigm combines three deeply interlocked dynamics: a long-run real-institutional process emerging from the re-structuring of the productive sector; a short-run financial process driven by the creation of credit at the roots of innovation; and a behavioural medium-run process emerging from the interaction between new financial behaviours and the institutional response (Perez 2002, 2009). This process of 'creative destruction', while instrumental in fostering a new socio-economic paradigm, could also lead to the obsolescence or the destruction of capital goods, financial assets and intangible capital of a firm or an entire sector, with potential systemic repercussions.

In the case of the low-carbon transition, the attention of the policy and academic community has recently focused on the possibility that the emergence of a carbon-free techno-economic system might lead several types of assets to become 'stranded'. These include physical and financial assets whose value would prematurely diminish because of the low-carbon transition, and would thus have to be entirely or partially written off the balance sheets of the companies that own them. The debate has so far mainly focused on fossil fuel companies, the portion of their reserves that would have to remain in the ground if a 2°C carbon budget would have to be respected, and the resulting potential loss in their market valuation (CTI 2013; McGlade and Ekins 2015; Meinshausen et al. 2009). More recently, the stress on climate-related risks for the financial system has been more strongly emphasized (Battiston et al. 2017; Prudential Regulation Authority 2015; Schotten et al. 2016). However, the potential impact of the process of low-carbon structural change on physical capital assets remains under-investigated. Despite some exceptions (Caldecott and McDaniels 2014; IRENA 2017; Pfeiffer et al. 2016), the analysis on the topic has been unsystematic and weakly connected to the rest of works on fossil fuels and financial assets.

This paper argues that, in order to develop a comprehensive assessment of the risks connected to a low-carbon transition, the integration of physical capital assets is a necessary step. In order to support our claim, we apply network analysis methods to identify structure in national accounts, and show that a move away from polluting resources and technologies is likely to produce a 'cascade of physical asset stranding', which might in turn lead to loss in value of financial assets.

Network theory has seen wide application in economics. It has been used to better understand the role of inter-sectoral dependency on the depth of business cycles (Blöchl et al. 2011; Acemoglu et al. 2012; Contreras and Fagiolo 2014), financial risk (Battiston, Farmer, et al. 2016; Battiston, Gatti, et al. 2012; Battiston et al. 2007), and international trade (Hausmann and Hidalgo 2011). More broadly, network theory informs the literature on economies as complex systems (Bak et al. 1993; Foster 2005), while viewing economies as networks is the foundation of Sraffian economics (Sraffa 1960; Aspromourgos 2004). However, empirical analysis of the network structure of economies has not addressed the biophysical basis of the economy and the one-way flow of materials from nature through transformation and production to final use (Ayres and Warr 2010; Hall and Klitgaard 2012). In this paper we propose new methods for analyzing the potential implications of a low-carbon transition, which would shift the biophysical underpinnings of modern economies, with potentially system-wide effects.

Starting from an input-output approach to the production process, we show how we can identify a cascade of potential physical assets stranding in France, starting from the mining and quarrying sector, propagating to chemicals and chemical products. This physical asset cascade is further complemented by adding financial assets and liabilities and hence a possible propagation into the financial sector. We argue that this highlights the importance of adopting a balance sheet approach for empirical analysis but also for dynamic modelling. The Stock-Flow Consistent approach, based on a rigorous accounting framework, is well adapted (and, we would argue, best adapted) to grasp the dynamics highlighted through our network analysis. To demonstrate its suitability, we use the results of a previous work that highlights the role of financial investors in shaping the transition towards a low-carbon economy, hence impacting the quantity and nature of stranded assets resulting from the transition.

The remainder of the paper is organised as follows. Section 2 presents the conceptual framework linking natural resources, physical capital and financial assets. Section 3 develops a method to identify 'basically central' economic sectors and applies it to the French economy. Section 4 focuses on mining sector to analyse how transition risks might propagate through the economic system. Section 5 discusses the balance sheet approach to macroeconomic analysis. Section 6 focuses in particular on how this approach could be incorporate into modelling. Finally, section 7 concludes.

2 A network of stranded assets

Three categories of assets at risk of climate-related stranding can be identified. All of them are deeply connected among each other, as exemplified in Figure 1.

[Figure 1 ABOUT HERE]

First, shifting to a carbon-free society would most likely require a portion of existing reserves of fossil fuels to remain unextracted. In a widely-cited paper, Meinshausen et al. (2009) argue that to keep within the internationally agreed target of limiting the global average temperature to at most 2°C above pre-industrial levels, just over half of the proven and economically recoverable reserves of coal, oil and gas must stay in the ground. Subsequent studies have found even tighter constraints (McGlade and Ekins 2015). These economically recoverable, but climatically dangerous, reserves were given the compelling name 'unburnable carbon' in a report by the Carbon Tracker Initiative (2011), which noted that if we wish to limit the chance of warming above 2°C to 20%, then we have a budget of 565 $GtCO_2$ from 2011 through 2050. By contrast, known fossil reserves, if combusted, would amount to 2,795 $GtCO_2$ – five times as much.

As Griffin et al. (2015) point out, the reserves are only unburnable if the associated emissions cannot be offset, either by carbon capture and sequestration (CCS) or by absorbing the carbon in forests and soils. However, relying on these technologies is a risky strategy. As of February 2014, CCS projects in operation or under construction around the world had a capacity of almost 40 $MtCO_2$ per year (Global CCS Institute 2014). Over the 40 years considered by Carbon Tracker Initiative, the total sequestration potential of these projects is 1.6 $GtCO_2$, a trifling amount compared to the need. Moreover, progress is slow, and CCS is unlikely to be commercially available in the near future (Nykvist 2013). Sequestration in forests and soils is also highly problematic and it is not obvious, with the current state of knowledge, that solutions will a) avoid unacceptable impacts and be both b) feasible and c) effective. Indeed, there are reasons to think that any given sequestration strategy will be problematic on at least one of these three dimensions (Kartha and Dooley 2016).

Second, long-lived capital assets (Shalizi and Lecocq 2009) may be put at risk by a shift in the physical basis of the economy. As thermodynamic systems far from equilibrium, economies and the societies of which they are a part are sustained by flows of accessible energy and materials that they degrade and release into the environment (Ayres and Warr 2010; Hall and Klitgaard 2012). Thus, ecological economists view the macroeconomy as having a direction, from raw materials, through processing, to intermediate use and then final use. As a consequence, any shift in the raw material inputs to the economy – including but not limited to a low-carbon transition – can affect multiple sectors. In Daly's (1995) formulation, natural resources are the bottom of an 'inverted pyramid'; most of the value generated in the economy is a multiplier of the comparatively small value added by the extractive sectors, and the capital stocks in the upper part of the inverted pyramid are put at risk when the resource base of the economy changes. Relevant examples include the stock of fossil-fueled power generation capacity, physical capital used in carbon-intensive industrial processes, transportation infrastructure, and others.

Third, all the natural resource and man-made capital stocks at risk of stranding are owned by private companies or governments, whose balance sheets might be deeply affected if their assets are written off before planned, with potential financial instability effects. If investors are inappropriately assessing the value of firms heavily invested in fossil reserves or fossil-intensive capital stocks, then in future those companies may suffer a large and abrupt loss in value. That loss could then propagate through the financial system, potentially sparking a crisis (Battiston, Mandel, et al. 2016). HSBC Global Research (2013) notes that most reserves are undeveloped, so the value of reserves at risk is a lower proportion than the volume of reserves at risk. But they argue that a fall in price due to reduced demand for fossil carbon would lower the value of developed reserves, potentially creating an even larger risk to the sector than the unburnable reserves.

These three categories of assets at risk of stranding are deeply interconnected and should be analyzed in a systemic way. However, the literature on stranded assets has so far strongly focused on fossil fuel reserves or on financial assets, and relatively less on long-lived capital assets. The challenge that these assets present to climate mitigation has long been recognized (England 1994; Ha-Duong, Grubb, and Hourcade 1997; Shalizi and Lecocq 2009; Erickson et al. 2015) but, with some exceptions (IRENA 2017; Pfeiffer et al. 2016), their role as potentially 'stranded assets' has not been examined. If they cannot use the resources they rely on for their operation, and if they cannot be easily modified to accept substitutes, then they may be abandoned, valuable only as scrap.

The challenge of transforming the structure of an economy is not new to economics. It is central to the ideas of Schumpeter and was a recurring theme in development theory, giving rise to a variety of 'structuralist' approaches (Chenery 1975). One lesson from that work is that generic structures – traditional vs. modern labor, agriculture vs. industry, worker vs. capitalist, backward vs. advanced regions, core vs. periphery – are useful for broad theorizing, but at a practical level, identifying structure is an empirical task.

3 Finding structure in highly-interconnected economies

Economic accounts present challenges for a network analysis. Inter-industry matrices are typically dense at the two-digit (or even three-digit) level and have nonzero entries on the diagonal. That is, every sector sells to and buys from nearly every other sector, as well as selling to and buying from itself. Moreover, purchases are not equal to sales between sectors, so the direction of payments matters. To distinguish between more and less important links in the dense network of inter-industry exchanges, network analysis in economics uses the magnitude of those exchanges. Together, these observations suggest that inter-industry matrices represent dense, weighted, directed networks with self-loops.

Prior analyses have used weighted centrality measures to judge the relative importance of sectors in the economy, but from a biophysical perspective, the existing centrality measures can be misleading. In a study of 39 input-output matrices, Blöchl et al. (2011) found, using a random walk centrality measure, that the highest centrality was in wholesale and retail trade in 26 samples (67%), while construction was most central in another four (10%), together accounting for over three-quarters of the samples. These results make sense, as trade and construction are general services used by all sectors of the economy in the normal course of business. As a consequence, they are revisited numerous times as goods and money circulate through the economy. However, raw materials extraction and processing sectors are not central in the sense that they are frequently visited; rather, they are central because they are a *sine qua non* of any production whatever. Indeed, the one-way flow of materials and energy imposed by thermodynamics means that those sectors will typically *not* be revisited. Thus, these sectors should have a low random walk centrality score.

Raw materials extraction and processing are expected to have strong forward links and weak backward links. Forward and backward links are conventionally measured using the Hirschman-Rasmussen index (Hirschman 1958; Rasmussen 1956). We apply the definition used by Górska (2015), which involves the Leontief inverse as computed from the inter-industry matrix and final demand. The measure of forward linkages is the row sum of the Leontief inverse, while the measure of backward linkages is the column sum of the Leontief inverse. The difference between the forward and backward linkages should be high for raw materials sectors.

We thus expect to find, for extractive and processing sectors, that they have both a large preponderance of forward over backward linkages and that they should have a low random walk centrality score. That is, they should be peripheral in the circular flow of goods, but on the input side rather than on the side of final demand. We call this combination of features *basic centrality*, and sectors with these features 'basically central' sectors. Figure 2 shows random walk centrality plotted against net forward linkages (the difference between forward and backward linkages) for France at the 63-sector level, where only those sectors with positive net forward linkages are shown. (See the appendix for sector codes.) As seen in the figure, the most basically central sector, located in the bottom right, is B: Mining and quarrying. Fisheries (A03) also appear, while forestry (A02) has a somewhat greater random walk centrality. Perhaps surprisingly, A01 (agriculture) does not appear on the graph. This is because A01 has negative net forward linkages, reflecting the fact that agricultural in France is highly input-intensive, making extensive purchases of machinery, fuel, and chemicals.

[Figure 2 ABOUT HERE]

4 Cascades of assets in physical production

The analysis leading to Figure 2 is evidence in the flow of inter-industry expenditure that the basically central sector B (Mining and quarrying) sits at the base of the economy – an empirical representation of Daly's (1995) 'inverted pyramid'. However, the density of the inter-industry matrix presents a problem. If we were to look for nearest neighbors to sector B we would find that nearly all sectors are in its neighborhood, in the sense that there is some payment, however small, between sector B and most other sectors. We deal with this by constructing a *minimal fully connected network*, by setting a threshold for inter-industry exchanges (regardless of direction) equal to the largest value that leaves the network fully connected once exchanges below the threshold are set to zero. Applying that procedure to the data for France gives a threshold value of 460 million Euro, which excludes 86% of the entries.

The inverted pyramid is illustrated in Figure 3 using the minimal fully connected network, with sector B (Mining and quarrying) at the base. The nearest neighbors to sector B are shown in the row just above it, the nearest neighbors of the nearest neighbors in the next row, and so on. The sector labels are staggered in each row so that they do not overlap. The final row, at the top of the figure, is not in any neighborhood of mining and quarrying in the minimal fully-connected network, but those sectors are connected to other sectors, as shown in the diagram.

[Figure 3 ABOUT HERE]

The connections shown in Figure 3 illustrate the central point made in this paper: that assets put at risk in a low-carbon transition are not limited to the extractive sectors. In the figure, the extractive sector is sector B (Mining and quarrying). The nearest neighbors to sector B in Figure 3 are C20 (Chemicals and chemical products), C23 (Other non-metallic mineral products), and F (Constructions and construction works). The presence of C23 and F show that at least part of the output from sector B is for non-fossil raw materials. The sectors that might be impacted by a low-carbon transition are those supplied by sector C20, which provides goods to A01 (Agriculture), C10-12 (Food, beverages and tobacco), C19 (Coke and refined petroleum), C21 (Pharmaceuticals), C22 (Rubber and plastics), D (Electricity, gas, steam and air conditioning), and F (Construction).[1] Thus, transforming the physical basis of the economy potentially puts a cascade of sectors – and their associated assets – at risk.

The concept of a cascade of assets informs how a low-carbon transition might affect the economy. As an illustration, we focus on agriculture (sector A01) and mining and chemical (sectors B and C20). These are shown in the 'Current Structure' in Figure 4. Following the network links illustrated in Figure 3, outputs from sector B flow to sector C20, which feeds into several sectors, including agriculture. In a low-carbon economy, chemicals are more likely to be based on agricultural materials (Hermann, Blok, and Patel 2007). This implies a substantial transformation of the economy, as illustrated in 'Low-carbon Structure' in Figure 4. In the Low-carbon Structure, sector A01 provides raw material inputs to sector C20, but it also takes outputs from that sector. The role of sector B is diminished, although it continues to provide minerals. The shift puts assets in sectors B and C20 at risk, as existing chemical plants based on fossil feedstock are re-tooled or replaced by 'bio-refineries' (Sanders et al. 2007). The shift also impacts upon food production and agriculture (Mathews 2009).

[Figure 4 ABOUT HERE]

In 2010, total fixed assets, of all kinds, in sector B (mining and quarrying), were 13.2 bln Euro for France in 2010[2]. In contrast, total fixed assets in sector C20 (chemicals and chemical products) was 58.9 bln Euro, more than four times larger. The same observation can be made for the total liabilities in sector B (48.5 bln Euro) versus total liabilities in sector C20 (82.1 bln Euro, twice as large) or for the total debt of the two entities: 14.3 bln Euro vs. 39.4 bln Euro. Thus, focusing on the extractive sector alone gives a misleading picture of the total value of real assets at risk in a transition to a low-carbon economy.

[1] The appearance of sector C19 (Coke and refined petroleum) downstream of C20 (Chemicals and chemical products) is surprising, but may represent the structure of France's petrochemical industry, in which some large firms (such as Total) are vertically integrated, producing both petroleum and chemicals.

[2] Using publically available statistics from INSEE (Institut national de la statistique et des études économiques) and ÉSANE (Élaboration des Statistiques Annuelles d'Entreprises).

Looking in more detail into the dynamics of these two sectors (see Figure 5) we can already observe interesting dynamics and characteristics with a structural disappearance of the mining and quarrying sector and a growth of the end-product sector (C20) . Sector C20 displays a shortening of capital lifecycle (from around 8 years to around 6 years), typical of the IT revolution, and fairly low capital intensity.

[Figure 5 ABOUT HERE]

This seems to indicate that the two sectors are relying on importation of raw material and hence are sensitive to any change of extraction process decided elsewhere. Should the mining sector be targeted for industrial policy aiming at changing the production process, the end-product sector would need most attention with a relatively short-term transition (5-10 years to renew existing capital stocks).

Employment dynamics indicate an overall decrease in hours worked with more than 50% over the last 40 years which is typical for an advanced economy. Yet, there are still more than 200,000 jobs at risks in the two sectors. Should most of these jobs disappear, a third wave of stranded assets could appear as households-related sectors (think of the mortgage industry or final goods producers) could be in trouble.

5 Adopting a balance sheet approach

Section 4 has discussed the potential relevance of the stranding of physical capital assets during the transition to a low-carbon economy. As already stated, this process is likely to have deep impacts also on the financial assets issued by the sectors affected, whose value might decrease, negatively affecting banks and financial investors. In turn, the stranding of financial assets might lead to a reduction in credit availability, depression of investments and a vicious spiral of defaults. This eventuality is exacerbated by the strong interconnectedness of modern financial systems and the high financialisation of the energy sector (Jerneck 2017).

In order to understand the issue in its complexity and formulate adequate policies to manage it, a comprehensive analysis must be developed, looking at all the interlinkages shown in Figure 1. At the moment, such a systemic perspective is missing, both in the dynamic modelling literature and in the literature developing empirical assessments of the exposure to climate risks. Several steps are needed to achieve a dynamic view on the issue: first, an assessment of natural capital assets; second, an assessment of physical capital assets used to produce intermediate and final goods; third, an assessment of their capacity utilisation; and fourth, an assessment of financial assets and liabilities, and how these are linked to the real economy. In other words, in order to understand the deep ramifications of the emergence of stranded assets and capture the multiple feedback mechanisms at play, we need to study more closely the balance sheets of financial and non-financial firms, governments, and households, and how these are connected in networks.

A balance sheet is a snapshot at a certain time of the financial situation of an economic agent. Two balance sheets measured in time t and $t+1$ are connected to each other through income and financial statements. The continuum of balance sheet-income and financial statement-balance sheet depict an intrinsically dynamic process. Indeed, balance sheet items (e.g. capital goods, land or financial assets) will generate income and expenditure flows (e.g. profits, maintenance costs or interest payments), which will impact other balance sheet items, say deposit accounts, credit lines or cash holdings. We can thus see how this dynamic process creates evolving multi-layered networks.

Many authors have stressed the importance of balance sheets to understand macroeconomic dynamics. Koo (2011; 2013) argues that firms change their profit optimization behavior towards debt minimization when their balance sheets are damaged, leading to a reduction in investment and spending. This generates what Koo calls a Balance Sheet Recession. He then calls for fiscal stimulus in order to repair the private sector corporation. Allen et al. (2002) highlight the roles of risks buried in balance sheets (such as maturity mismatches or capital structures mismatches) in explaining recessions but also, following the work of Krugman (1999) on open economies, in countering the productivity gains that a currency depreciation could create. The role of deleveraging and cross border capital flows in crisis triggering and diffusion are highlighted in Allen et al. (2002), Lane (2013), and Bruno and Shin (2013). Finally, Caballero (2016), analyzing the factors explaining the emergence of banking crises, shows how not only lending booms are important but also portfolio-equity inflow bonanzas, even in the absence of lending booms. He thus indicates a new channel of financial fragility based on asset price inflation through foreign portfolio investment. Most of these authors also stress the importance of looking at net and gross flows, and at the nature of the flows as these might indicate different dynamics and the emergence of different type of risks.

In the case of stranded assets, the balance sheet approach could be fruitfully applied to both the empirical assessment of the value of assets at risk of stranding and the development of theoretical and numerical models aimed at analyzing the macroeconomic and financial repercussions of a low-carbon transition.

To our knowledge, Battiston et al. (2017) is the most advanced attempt to develop an empirical assessment of stranded assets risk. The paper develops a ‘climate stress-test’ for the financial system of the European Union and the United States looking at the exposure of banks and financial investors to climate-related risks through equity holdings and loan portfolios. Using the DebtRank methodology (Battiston, Puliga, et al. 2012) they are able to capture also the second-order effects of the stranding of financial assets propagating throughout the financial system. While providing an innovative assessment of direct and indirect exposure to climate risks, the analysis does not cover the totality of network effects that a low-carbon transition might trigger. Going back to Figure 1, Battiston et al. (2017) focus on the financial side of asset stranding in the upper half of the figure.

However, the analysis presented in this paper indicates that a second type of indirect effects should be accounted for. These indirect effects propagate through the network described in input-output matrices. As we have argued above, not only basic sectors such as the mining and extracting sector would be impacted by a reduction in oil extraction but also some of the downstream sectors such as ‘chemicals and chemical products’. These sectors face the possibility of having physical stranded assets (i.e. obsolete machinery) or increased costs of production which could jeopardize their ability to meet financial requirements such as interest payments or dividend distribution, thus creating a new source of financial stranded assets. These new financial stranded assets could further deteriorate financial institutions’ balance sheet and create more second round effects.

6 Stock-Flow Consistent models and stranded assets

In addition to empirical assessments of climate-related risks, there is the need to develop sound modelling tools to analyze the systemic implications of a low-carbon transition, and study appropriate policy responses. The balance sheet approach to the study of natural, physical and financial assets is not easily implemented in numerical modelling. In the climate economics literature, Integrated Assessment Models (Nordhaus 2013; Emmerling et al. 2016), while often offering a detailed representation of capital stocks on the energy and environmental side, usually lack a disaggregated representation of productive capital stocks, do not consider the fluctuations in their capacity utilisation, and entirely abstract from financial assets and liabilities (Mercure et al. 2016). In the macroeconomic dynamics literature, on the other hand, Dynamic Stochastic General Equilibrium (DSGE) models typically ignore both natural capital assets and the banking and financial system[3]. They are thus unable to grasp the complexity of the network of dynamic interactions among different forms of balance sheet items.

An alternative to these methodological approaches is offered by Stock-Flow Consistent (SFC) models (Godley and Lavoie 2012; Caverzasi and Godin 2015). SFC models use balance sheet dynamics to structure the macroeconomic interaction between sectors and assets. As such, the approach details sectoral flows typical of the sectoral accounts found in the system of national accounts. The emerging accounting framework thus ensures that every flow has an origin and a destination and leads to an increase or a decrease of two stocks (one in the originating sector and one in the destination sector), thus following Copeland's (1949) quadruple entry system. Being inherently based on the depiction of physical and financial assets, SFC modelling is thus capable of satisfying the four conditions required to develop a proper analysis of asset stranding mentioned in Section 5. The inclusion of financial assets of different types is a particularly relevant value added of this methodology.

6.1 Monetary theory of innovation

Schumpeter (1939) describes credit as the monetary complement of innovation. It is thus essential to understand how credit emerges and its relation with money. A fundamental point is that, "*in the modern economy, money is [...] a financial asset*" (McLeay, Radia, and Thomas 2014), and if money is a financial asset for someone, it has to be a financial liability for someone else. Most of the money circulating in modern economies is in the form of bank credit (Ryan-Collins et al. 2011). Moreover, banks are relatively autonomous in this process of credit creation, and do not require either central bank reserves or customer deposits in order to lend (Deutsche Bundesbank 2017). Thus, commercial banks should not be seen as mere intermediaries but as active players in determining the quantity of money in the economy. Yet, as important money is, other financial assets play important roles in shaping macro-economic dynamics. In a monetary economy, agents are closely interrelated through a complex evolving network of financial assets and liabilities, recorded in their balance sheets. Decisions undertaken by individual agents, and resulting in a variation of their balance sheet, affect other agents' balance sheets, both directly and indirectly. This is what SFC modelling captures.

We argue, with Caiani et al. (2014a, 2014b), that the SFC approach is best fitted to grasp the complex dynamics emerging from evolutionary processes such as the transition to a low carbon economy, in a highly financialized economic system. Schumpeter showed how innovation modifies i) production process structure, ii) industrial market structures, iii) labor markets, iv) income distribution, and v) consumption patterns. Because SFC models track down inter-sectorial relationships either directly via monetary flows (in a way similar to Input-Output tables) or indirectly through financial assets network, they allow analyzing in a pervasive way the effects of technological change. For this reason, it appears particularly appropriate to analyze the interdependencies between technological change – affecting labor and capital productivity – and its finance. In particular, the use of a multi-sectorial SFC modeling approach allows handling the repercussions of technological change on different social groups and sectors such as distribution, intra-sectorial labor and wages movements and structural changes.

Furthermore, the accounting framework and its relation to time allow us to highlight key interactions between sectoral transactions in the short and long run, an important feature when modelling transition dynamics, as argued by Perez (2010). As already explained, SFC models are built on a framework very similar to national accounts where flows in each period are interconnected via balance sheets items. This leads to, paraphrasing Robinson (1956), seeing the long-run as a collection of short-run interactions. This

[3] Though there has been some recent work to introduce more financial frictions or endogenous money, see the work of Brunnermeier et al. (2012) or Benes et al. (2014), for example.

is crucial as one fundamental aspect of the transition is its path-dependency. It is thus key to understanding the difference between slow or quick transition processes, in the short run and in the long run.

So far, the SFC modelling approach has been applied to environmentally-related problems only a handful of times (Monasterolo and Raberto 2018; Dafermos, Nikolaidi, and Galanis 2017b, 2017a; Berg, Hartley, and Richters 2015; Bovari et al. 2017), and in only one occasion to the stranded assets issue (Campiglio, Godin, and Kemp-Benedict under review).

6.2 An SFC model of stranded assets

The preceding analysis and discussion leads us to view a low-carbon transition as a change that can leave assets stranded across the productive economy, and not merely in the extractive sector and the associated reserves. In a separate paper (Campiglio, Godin, and Kemp-Benedict under review), we document a Schumpeterian stock-flow consistent model for studying a low-carbon transition. Compared to the detailed sector view in the empirical 'inverted pyramid' shown in Figure 3, the model has only three sectors: high-carbon capital goods, low-carbon capital goods, and consumer goods. There are two households: one (wage-earners) that receives wages and keeps money in the bank; and another (financial investors) that holds equity stock in firms and receives dividend payments. Financial investors determine the value of equity through their demand, which is influenced but not fully determined by expected returns. Rather than responding fully to returns, financial investors have biases and cognitive limitations that lead them to underestimate the value of low-carbon investments in the transition, and overestimate the value of high-carbon investments.

The model assumes the ideal case of a transition towards low carbon capital due to lower prices in order to highlight the important role of financial investor in shaping the transition. The model stresses the emergence of a cascade of physical and financial stranded assets as the consumption sector start divesting from high-carbon capital to low-carbon capital on the one hand, and as financial investor decide to invest in the green sector rather than in the conventional one. Because our financial investors face radical uncertainty they have to rely on their perception to build expectation on the value of financial assets. However these perceptions might be tainted by disbelief or measurement errors leading to financial investor to overvalue high-carbon financial equity and undervalue low-carbon equity. This leads to more physical and financial stranded assets or even to no transition at all, highlighting the power of financial investors' opinions in determining the shape – or existence – of a low-carbon transition.

7 Conclusions

The transition to a low-carbon society is likely to have a negative impact on all the economic sectors that base their production on emission-intensive resources and technologies, whose assets – reserves of natural capital and stocks of physical productive capital – might lose part of their value and be written off their balance sheets. The stranding of these assets will propagate to the rest of the economic system through two strongly interconnected channels. First, the value of the financial assets issued by these carbon-intensive sectors – equities, bonds, loans – is likely to drop, affecting the balance sheets of the financial institutions holding them, as highlighted in the literature on climate stress-tests. This might create a cascade effect of stranded financial assets through the deeply interconnected financial network. Second, the physical capital assets of all the downstream sectors that employ carbon-intensive products might also become stranded, with potential repercussions on their production and the assets of the downstream sectors, and so on. This complexity requires that stranded assets be assessed from a systemic perspective, which, however, the related literature has not yet achieved. In particular, while several analyses have been developed to understand and estimate both the natural and financial assets at risk of stranding, little has been written about physical capital assets.

This paper contributes to filling this gap by developing an analysis of national input-output tables, using France as a case study. First, we propose a novel measure of 'basic centrality' to identify sectors that play a particularly relevant role in the economic network from a biophysical perspective. Primary resource sectors appear to be positioned at the very core of an 'inverted pyramid' of inter-sectoral connections. Second, we construct a 'minimal fully connected network' to study the channels through which moving away from fossil fuels is likely to affect the rest of the economic system. We find the chemical sectors to play a particularly significant role in the potential cascade of stranded physical capital assets.

Finally, we have argued that, in order to be able to capture the dynamic links between natural, physical and financial assets, the analysis must be inherently based on the study of balance sheets. This can be applied with promising results to both the empirical assessment of climate-related stranding risks and the development of modelling tools for scenario and policy analysis.

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Figure 1: Natural, physical and financial assets at risk of stranding

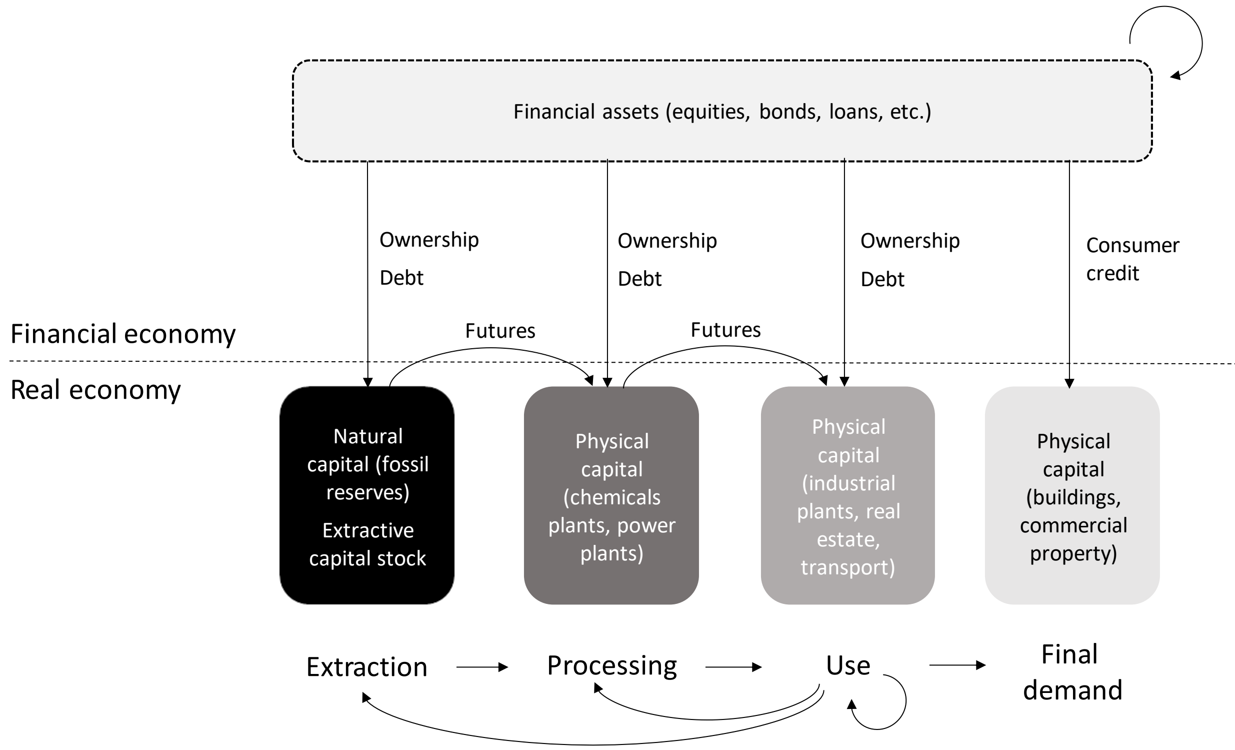


Figure 2: Random walk centrality vs. net forward linkages for sectors with positive net forward linkages from the 2010 63-sector symmetric input-output matrix for France

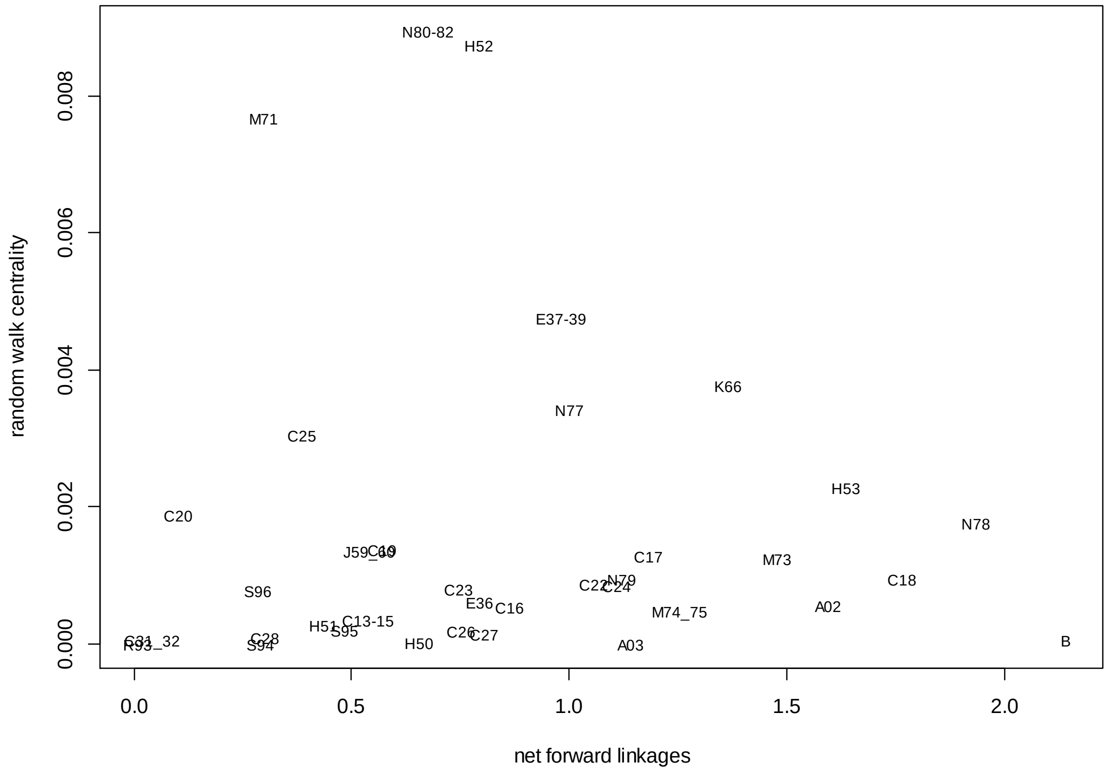


Figure 3: The inverted pyramid: Minimal fully-connected network with sector B (Mining and quarrying) at the base

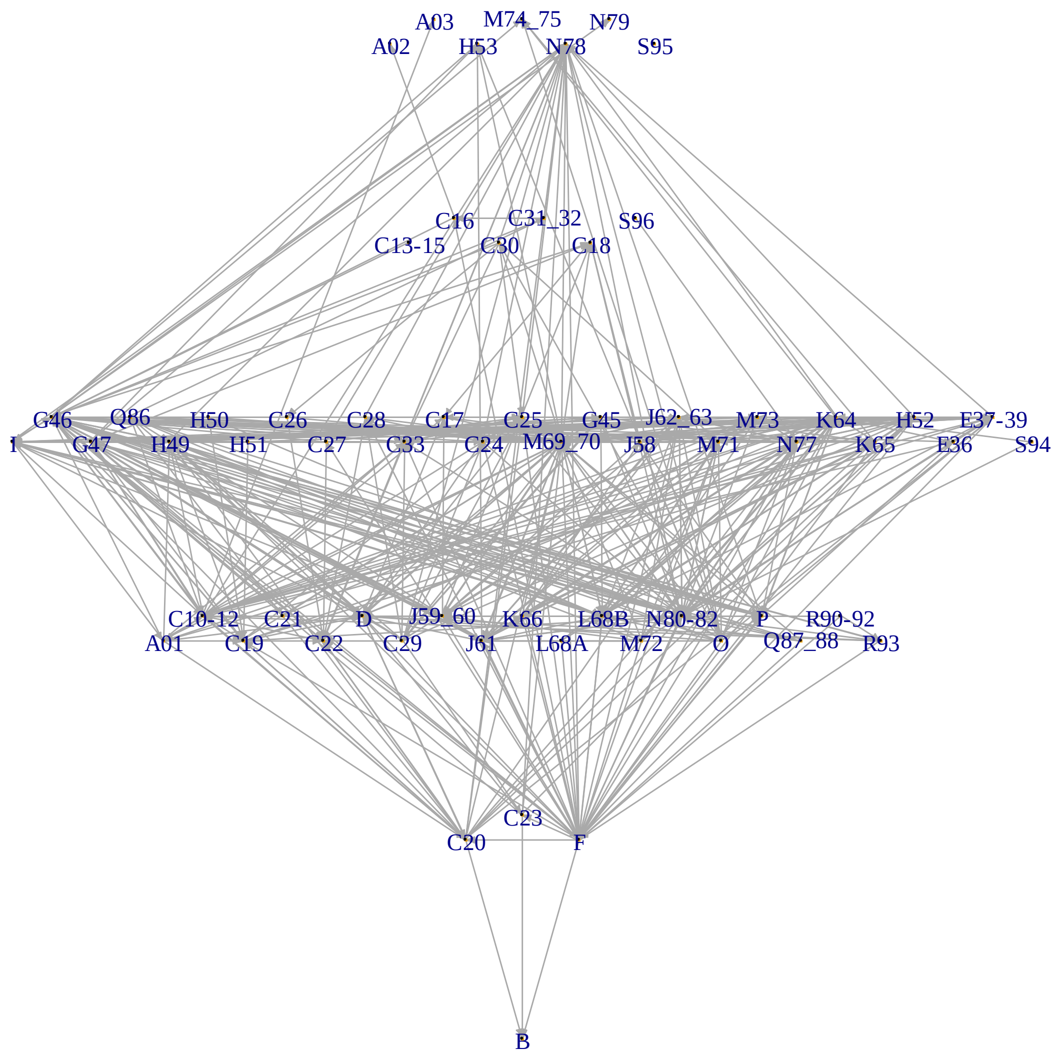


Figure 4: Changing structure in a low-carbon transition

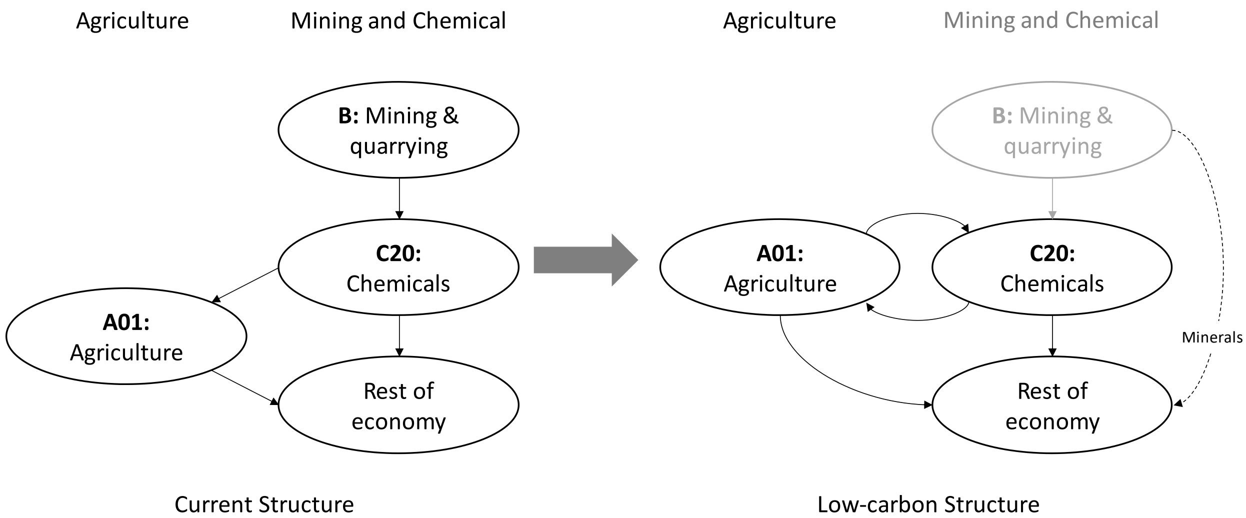
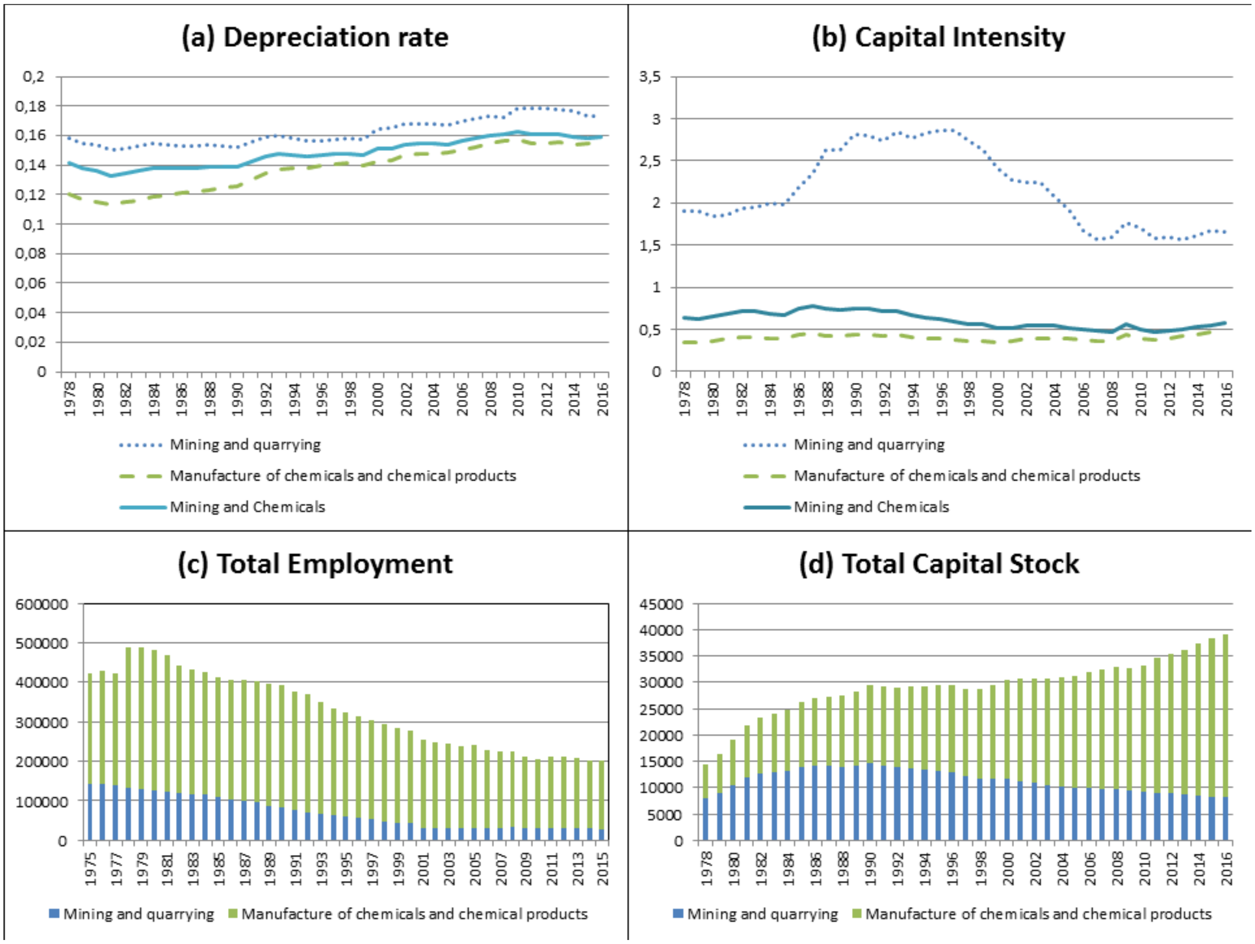


Figure 5 : Capital and Labor characteristics of the Mining meta-Sector, source Eurostat (nama_10_a64_e, nama_10_a64, nama_10_nfa_st) and authors' computations.



9 Appendix: Sector codes

Code	Description
A01	Products of agriculture, hunting and related services
A02	Products of forestry, logging and related services
A03	Fish and other fishing products; aquaculture products; support services to fishing
B	Mining and quarrying
C10-C12	Food, beverages and tobacco products
C13-C15	Textiles, wearing apparel, leather and related products
C16	Wood and of products of wood and cork, except furniture; …
C17	Paper and paper products
C18	Printing and recording services
C19	Coke and refined petroleum products
C20	Chemicals and chemical products
C21	Basic pharmaceutical products and pharmaceutical preparations
C22	Rubber and plastic products
C23	Other non-metallic mineral products
C24	Basic metals
C25	Fabricated metal products, except machinery and equipment
C26	Computer, electronic and optical products
C27	Electrical equipment
C28	Machinery and equipment n.e.c.
C29	Motor vehicles, trailers and semi-trailers
C30	Other transport equipment
C31_C32	Furniture and other manufactured goods
C33	Repair and installation services of machinery and equipment
D35	Electricity, gas, steam and air conditioning
E36	Natural water; water treatment and supply services
E37-E39	Sewerage services; sewage sludge; waste collection, treatment and disposal services; …
F	Constructions and construction works
G45	Wholesale and retail trade and repair services of motor vehicles and motorcycles
G46	Wholesale trade services, except of motor vehicles and motorcycles
G47	Retail trade services, except of motor vehicles and motorcycles
H49	Land transport services and transport services via pipelines
H50	Water transport services
H51	Air transport services
H52	Warehousing and support services for transportation
H53	Postal and courier services
I	Accommodation and food services
J58	Publishing services
J59_J60	Motion picture, video and television production, sound recording, broadcasting, …
J61	Telecommunications services
J62_J63	Computer programming, consultancy and related services; Information services
K64	Financial services, except insurance and pension funding
K65	Insurance, reinsurance and pension funding services, except compulsory social security
K66	Services auxiliary to financial services and insurance services
L68A	Imputed rents of owner-occupied dwellings
L68B	Real estate services excluding imputed rents
M69_M70	Legal and accounting services;Services of head offices; management consulting services
M71	Architectural and engineering services; technical testing and analysis services

Code	Description
M72	Scientific research and development services
M73	Advertising and market research services
M74_M75	Other professional, scientific and technical services and veterinary services
N77	Rental and leasing services
N78	Employment services
N79	Travel agency, tour operator and other reservation services and related services
N80-N82	Security and investigation services; buildings and landscape; office support services
O84	Public administration and defence services; compulsory social security services
P85	Education services
Q86	Human health services
Q87_Q88	Residential care services; social work services without accommodation
R90-R92	Creative, arts, entertainment, library, museum, *etc.*; gambling and betting services
R93	Sporting services and amusement and recreation services
S94	Services furnished by membership organisations
S95	Repair services of computers and personal and household goods
S96	Other personal services
Not used	
T	Services of households as employers; goods and services for household own use
U	Services provided by extraterritorial organisations and bodies