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Review

Stranded assets and stranded resources: Implications for climate change mitigation and global sustainable development

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ABSTRACT

The Paris Agreement's 2 °C objective requires that more than 80% of all proven fossil fuel reserves become stranded resources, and investments in such resources may become stranded assets for industrialized and developing countries. The literature scarcely covers the implications of stranded assets and resources for 'latecomers' to development. Hence, we address the question: What does a literature review of stranded resources and stranded assets in a diversity of fields imply for latecomers to development in the fields of climate change and global sustainable development? We find seven dimensions in the literature: (i) Spatial: where first comers use their own resources and resources of other countries for their own development leaving little environmental utilization space for latecomers to develop; (ii) Technological: when first comers 'dump' older technologies (stranded assets) on latecomers; (iii) Economic: when first comers avoid paying compensation for damage caused to latecomers or for the stranding of resources in latecomer countries; and first comers may potentially also indirectly transfer their soon to be worthless shares on latecomers; (iv) Ecological: when knowledge from first comers may prevent latecomers from using their resources/ or may accelerate the rate at which their resources and assets become stranded; (v) Political: when first comers refuse to take environmental action claiming that latecomers are not doing so; while latecomers may claim that first comers should take action first; (vi) Legal/ Policy: when investments in resources and assets in a globalizing world involve long-term contracts protected under private law may cause policy freezing and liabilities in latecomers; and (vii) Social: when latecomers adopt different notions on development than first comers. Latecomers need to be sensible in deciding which resources to develop to avoid carbon lock-in and whether phasing-in renewables could avoid creating stranded assets in the first place.

1. Introduction

With the adoption of the Sustainable Development Goals (SDGs) [1] and the Paris Agreement [2] climate change has to be addressed within the context of sustainable development without compromising on social and economic goals as these are framed as interconnected and indivisible. The Paris Agreement's 2 °C objective requires a carbon budget of cumulative greenhouse gas (GHG) emissions that cannot be exceeded ([3], p. 13; [4]). With a 50 per cent probability of meeting the 2 °C objective, the budget for 2011–2050 is around 1100 GtCO2 (gigatonnes of carbon dioxide), while global fossil fuel reserves hold around three times this amount and fossil fuel resources hold significantly more [4]. This implies that 33% of oil, 49% of gas and 82% of coal reserves need to remain underground [4]. With an 80% probability, the carbon budget is 565 GtCO2 and only 20 per cent of fossil fuel reserves can be extracted [5]. The 1.5 °C target translates into an even smaller carbon budget. The newest IPCC report [6] argues that achieving 1.5 °C could save 1.5–2.0% of Gross World Product (GWP) by 2050 and significantly more by the end of the century. This would also enhance the ability to achieve sustainable development and the SDGs, following transformative development that balances social, economic and environmental concerns and meets the needs of the present and future generations [7].

Thus, meeting the Paris objective requires turning fossil fuel reserves into stranded resources and existing investments into stranded assets. In this paper we define stranded assets as assets that lose economic value well ahead of their anticipated useful life, whether that is a result of changes in legislation, market forces, disruptive innovation, societal norms, or environmental shocks (cf. [8], p. 1, see 2.3) and we define stranded resources as 'resources which are considered uneconomic or cannot be developed or extracted as a result of

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technological, spatial, regulatory, political or market limitations, or changes in social and environmental norms' (see 2.4). We argue that the issue of stranded assets and stranded resources has implications on countries' right to development [9] or right to promote sustainable development [10,11]. Looking at fossil fuel assets and resources, based on economic modelling looking for the most economically efficient outcome (without carbon capture and storage (CCS)), Africa will have to leave 26%, 34% and 90% of gas, oil and coal reserves untouched, China and India – 25%, 53%, and 77%, and the rest of Asia, excluding the Middle East, 12%, 22% and 60% respectively [4], implying huge losses to these countries. Developing countries such as Mozambique, Kenya, Tanzania, Ghana, Uganda, Senegal, and Côte d'Ivoire, have recently discovered such fossil fuel resources [12] and hope to become rich economies. Yet, these newcomers to fossil fuel investments face the risk of creating new stranded assets. The average lifetimes of electric power-generating fossil fuel plants range between 35–40 years [13], while oil and gas plants can last up to 55 years and coal plant lifetimes can be 75 years [14]. At the same time, investments in infrastructure distribution enabling the use of fossil fuels also have different lifetimes as they generally require long-term investments. Phasing out these society-wide investments prematurely has huge economic consequences. Of course, rich countries will also face economic losses. For example, the Dutch government's decision to leave gas underground in the province of Groningen not only leads to losses for the government, for the parties (Shell, ExxonMobil and NAM (Dutch Petroleum Company)), but also for home-owners who need to redesign their houses to make them less dependent on gas. However, this paper does not focus at the costs for industrialized countries which is being covered in other papers.

Although CCS and geoengineering may reduce the pressure for a fossil fuel phase out [15,16], negative emission technologies (such as afforestation, direct air capture of CO_2 or enhanced weather) will not alter the carbon budget and deploying these technologies is not easier than mitigating emissions [17]. Besides, the slow deployment of expensive CCS techniques [18,19], low oil and gas prices [20], the increasing price competitiveness of wind and solar energy [21], and the growing impacts of climate variability and change will only intensify the stranded assets threat [19].

So, who should (be allowed to) use the remaining fossil fuels? Latecomers to development use their resources later than industrialized countries and often use older and more affordable technologies. However, these countries are increasingly being asked to not use their resources or to phase out these older technologies because of their environmental impact. Many industrialized countries have deforested, built dams, and used fossil fuels to develop, but latecomers are being discouraged from engaging in these activities – thus limiting their scope to develop. At the same time, the argument that latecomers need to follow in the footsteps of the industrialized countries is problematic environmentally as the window for addressing many environmental challenges is closing rapidly; the health impacts of environmental problems are significant [22]; climate-related risks to, among others, food security, livelihoods, water supply, or human security are increasing [6]; and the economic benefits of investing in fossil fuels are undermined by the challenge of stranded assets in addition to the high costs of adaptation to climate change or declining pollinators.

While there is considerable literature on the economic, and to a lesser extent, social aspects, this paper looks at whether the literature on stranded assets has implications for the relations between first comers and latecomers in light of the climate change issue. It addresses the question: What does a literature review of stranded resources and stranded assets in a diversity of fields imply for latecomers to development in the fields of climate change and global sustainable development?

In doing so, we combine two fields of knowledge – stranded assets/resources and the international (sustainable) development studies literature in the field of climate change. This is innovative as (a) there are no review studies looking at the concept of stranded assets/stranded resources within academic literature in a diversity of fields, going beyond the issue of the carbon budget, fossil fuels or climate change, and as (b) much of the literature focuses on the consequences of stranded assets for investors or financial institutions but does not assess the issue from a global sustainable development perspective addressing the interplay between rich and poor countries discussing the impacts for latecomers to development.

This paper thus takes a 'first comer-latecomer' perspective, building on development economics' literature that focuses on the empirical challenges latecomers face in processes of 'catching up' (e.g. [23–26]). In the development studies literature, some refer to this divide as the 'Global North' versus the 'Global South'. We characterize developing countries as latecomers to development versus developed or industrialized countries which were first comers to development and were able to use resources that are now increasingly becoming stranded (e.g. carbon-intensive resources). We recognize that 'developing countries' do not constitute a homogeneous group (nor do 'industrialized countries'), having different levels of development. However, for analytical reasons this divide serves a purpose and, when necessary, we differentiate using the concept of 'emerging economies'. From the first comer-latecomer perspective we examine the impacts for global sustainable development based on the principles of the Right to Development, the Right to Promote Sustainable Development, and the Common but Differentiated Responsibilities and Respective Capabilities [11,9]. Thus, our position is to discuss the various challenges latecomers to development – cf. 'the developing world' – face with regard to climate change mitigation and stranded assets and stranded resources, keeping the equity principles of the Climate Change Convention central to our discussion. Our work is embedded within the SDGs framework, and this paper specifically tries to address the urgent action needed to combat climate change (SDG 13) while addressing global access to 'affordable, reliable, sustainable energy and modern energy' (SDG 7).

Hence, this review paper analyses the literature on stranded resources and assets in various fields (see 2); extracts strategies for dealing with stranded assets and resources (see 2.5); and discusses five main trends found in the literature (see 3). From the literature review this paper identifies and analyses seven first comer-latecomer dimensions related to the stranded assets issue (see 4.1); assesses the strategies found in the literature review in dealing with stranded assets in the context of global sustainable development (see 4.2); and draws conclusions (see 5).

2. Stranded resources and stranded assets

2.1. Introduction

We differentiate between stranded resources (a resource not used) and stranded assets (an asset that is losing/has lost value). For instance, oil resources can become stranded if they cannot be used; investments (assets) made to take out these resources (e.g. an oil refining plant or pipelines) become stranded if production must be stopped. Stranded assets are primarily a problem of countries, investors and consumers that have invested in a specific resource. Stranded assets can be investments, infrastructure, equipment, contracts, know-how and/or jobs. Stranded resources are briefly mentioned in the scholarly literature, but they are of particular importance for developing countries because new knowledge might require them to leave their resources untouched (see 4.1.4). This paper focuses on stranded resources including fossil and non-fossil fuel resources such as water, metals, or forests.

2.2. Method of the literature review

To answer the research question, we undertook a structured qualitative literature review on the concepts of stranded assets/stranded resources to understand the possible meanings and implications of the concepts from a diversity of fields. This enabled us to conceptualize encompassing definitions of the concepts, synthesize previous findings and identify gaps in the literature with regard to the first comer-latecomer dimension (see 4.1). Our review covers the literature from 1994 to April-2018 from academic and non-academic journals and databases. We first searched for the paired concept of 'stranded asset*' and 'stranded resource*' in the title and topic (Web of Science) or in the title, keywords or abstract of the article (Scopus); then expanded the search to 'all fields' in Scopus; then abandoned the coupling criteria and searched; and then expanded the search in the grey literature. We reviewed all articles where the concept of 'stranded asset'/'stranded resource' was defined or described in the text and when they provided new elements to the definition or to the elaboration of the concept. We searched in the grey literature to ensure that no new aspects or insights – in the definition – were left out. Figs. A1 and A2 (Appendix A) display the occurrence of the concepts in the Scopus database's literature to show the concepts in terms of chronology and subject area.

2.3. Stranded assets, its definition and characteristics

We identified 1856 papers. We excluded irrelevant scientific fields,[1] scanned the remaining 837 articles, identified key grey literature (e.g. by Carbon Tracker) and shortlisted an example of a concept matrix with 29 publications for detailed review (see Appendix A, Table A1) based on whether the paper (a) defined the concept or (b) discussed (components of) the concept more in detail. The literature from the Scopus database is presented over time (see Appendix A, Fig. A1) and subject area (see Appendix A, Fig. A2).

Stranded assets can be traced back to Schumpeter's concept of creative destruction where assets become stranded through competition, innovation and economic growth [27,28]. They include financial (e.g. contracts), physical (e.g. plants, equipment, infrastructure) and immaterial assets (e.g. human capital, policy, technology) [29–31] and occur in industries [29] like the electricity supply industry where the focus of papers has mostly been on natural gas (e.g. stranded because of the high costs of pipelines for Liquefied Natural Gas (LNG) facilities) and nuclear plants (due to the introduction of competition in the electricity markets) [32].

Stranded assets are investments whose value falls (or 'sunk' assets whose profitability is lower than expected [33]; that are prematurely retired (e.g. [34,35]); that are subject to costly retrofitting [36]; or that become liabilities [37]. This can happen because of unforeseen, unexpected or non-anticipated changes in (i) the regulatory environment (e.g. policy changes or changing statutory interpretation) (e.g. [31,38–40]); (ii) market conditions (e.g. price shifts, uneconomic returns or competitive factors) [30,32,41]; (iii) societal norms or conditions (e.g. changing consumers preferences or certification schemes) [42,43]; (iv) technology (e.g. innovations in clean energy) [32,41]; (v) financial contexts (e.g. currency devaluation or unanticipated write-offs) [29,44,45]; and/or because of (vi) environmental risks (e.g. disasters or climate change) [44].

Table A1 (Appendix A) presents an example of a shortlist of 29 relevant publications showing the characteristics of stranded assets, the topics they are applied to and the chronology of the concept. We use Generation Foundation's definition of a stranded asset as 'an asset which loses economic value well ahead of its anticipated useful life, whether that is a result of changes in legislation, market forces, disruptive innovation, societal norms, or environmental shocks' ([8], p. 1) encompassing all characteristics of Table A1 (Appendix A).

2.4. Stranded resources, its definitions and characteristics

The literature review on 'stranded resources' yielded 18,223 articles. This list was reduced to 5741 articles[2] and an example of a shortlist of 21 relevant papers is shown in Table A2 (Appendix A). This list is made based on papers that defined the concept. Although the concept of stranded resource is used often, it is rarely defined or substantively reviewed. Figs. A1 and A2 (Appendix A) classify stranded asset/resource publications in terms of chronology and subject area.

Most articles on stranded resources concern natural gas resources (e.g. [46,47]) that are 'underutilized' ([48], p. 98) because of (i) technological constraints (e.g. offshore gas liquefaction technologies) (e.g. [49]); (ii) spatial remoteness (e.g. far from the market or offshore reserves) (e.g. [47,48,50,51]); and/or (iii) low commercial viability because of high extraction costs (e.g. fractured natural gas) [46,52], saturated markets [47], small mines [53,54], high transportation/pipeline costs (e.g. [49], or political limitations [55]. Within the stranded natural gas literature, the terms 'resources' and 'reserves' or 'fields' are often used interchangeably. Oil resources can be stranded because of 'reservoir geology, access to the field, or access to facilities for development' ([56], p. 48) leading to excessive costs. Non-fossil fuel resources such as renewable resources (e.g. wind, geothermal or biomass) are often stranded as they are/become uneconomic due to high technical or logistical costs (far away from end-users or lacking grid connection) (e.g. [57–59]), low economies of scale, and the seasonal nature of the resource (e.g. insufficient solar power in the winter) [60]. Speight ([61], p. 56) argues that stranded resources may not be stranded indefinitely as they are 'likely to be developed in the future when existing sources begin to deplete'. This is, for example, the case with some carbon-intensive unconventional oil and gas resources (e.g. shale gas or tar sands) that were stranded in the past but are being unlocked as a result of technological advancement [62].

Papers on stranded resources scarcely consider the impacts of climate change or the fact that global society is crossing planetary boundaries. The conceptual coverage of stranded resources expanded only recently: recognizing forests that are not converted as stranded resources due to climate change impacts or forest protection policies (e.g. [63,64]); the stranding of potential hydroelectric power due to legislation [42]; or the fact that climate policy will require the phase out of fossil fuel use (e.g. [4,10,65]).

Taking all the above aspects together, we define stranded resources as 'resources which are considered uneconomic or cannot be developed or extracted as a result of technological, spatial, regulatory, political or market limitations, or changes in social and environmental norms'. This definition applies to energy sources, but also to forests that are not converted or the potential water energy from large dams that are not built.

2.5. Dealing with stranded assets and stranded resources

A resource becomes an asset when it is commercially invested in and used. This asset becomes stranded when it is prematurely retired. Here we discuss the most recurrent strategies in the literature to deal with stranded assets and stranded resources. The stranded assets issue 'ultimately requires that somebody [..] pays for something that they don't receive. Deciding who pays will be a Solomonesque exercise' ([66], p. 59) and the cost of paying compensation for stranded assets will be a key challenge for policymakers (e.g. [29,40,67,68]). Governments' reaction to deal with those left with stranded assets (cf. transition policy) can be divided into roughly three categories: (a) full compensation; (b) partial compensation by exempting pre-existent investment from the

[1] Included fields of science within Scopus are business, management and accounting, decision sciences, earth and planetary sciences, economics, econometrics and finance, energy, (chemical) engineering, environmental science, materials science, agricultural and biological sciences, multidisciplinary, and social sciences. Excluded fields of science within Scopus are chemistry, mathematics, biology, medicine, computer science, physics, astronomy, and arts and humanities

[2] See footnote [2] for included and excluded fields of science.

new rule (cf. grandfathering, phasing-out); or (c) no relief for losses (e.g. focusing on phasing-in) (cf. [69,70]).

Compensation (full or partial) for stranded assets is a commonly proposed strategy (e.g. [68,71,72]) based on ideas of fairness towards the investor (e.g. [73,74]). Compensation can be (a) ex ante (before the stranding of assets), such as European countries' subsidies to coal-fired plants provided under the premise of their future closure [75]; or (b) ex post (after the stranding of assets) [76], such as the compensation the German government needs to pay to the nuclear energy companies after the parliament's decision to prematurely decommission all nuclear power plants (by 2022) following the Fukushima disaster [65].

A different example of international compensation is found in the 'Reducing Emissions from Deforestation and Forest Degradation' (REDD) mechanism where developing countries hope to be compensated for the opportunity costs (foregone benefits) of the stranding of their forest resources (see 3.4). Paying for stranded assets can also mean paying for the workers dependent on the stranded assets for their jobs (e.g. [41,64]). Stranded assets thus also include intangible assets – non-monetary assets without physical substance [73] – such as know-how and human capital.

A problem with these phasing-out strategies is that new technologies have a disadvantage against incumbent technologies as their cost and performance is more uncertain [77]. Besides, there is the risk of sustaining lock-in mechanisms through processes of grandfathering (when emitters are subject to less stringent standards) [70,78]. 'Carbon lock-in' effects – or 'positive feedbacks or increasing returns to the adoption of a selected technology' [77] – refer to the dominance, and the deep interdependence, of technological infrastructures with carbon-intensive technologies [79] inhibiting the transition to low-carbon technologies. Stranded fossil fuel assets potentially have large and long-term 'cascade effects' due to the deeply interconnected financial network of carbon-intensive sectors [80], creating stranded assets to sectors engaged in upstream and downstream activities, such as service firms (e.g. manufacturers of conveyor belts for mining), and all sectors that use fossil fuels as input (e.g. through the increased costs of electricity), especially firms in transportation, industrial and automotive sectors [81]. Carbon lock-in and the cost of dismantling fossil fuel infrastructure 'are expected to become a major economic burden for states and hence the tax payer' ([82], p. 18) as costs of stranded assets are often passed on to consumers [19], for instance, within the energy sector through the increased cost of electricity [81].

On the other hand, investment decisions should also be prudent and stranded resources and stranded assets are inherent to the process of disruptive innovation in competitive markets [73] (cf. Schumpeter's creative destruction, see 2.3). 'Firms incur losses and either adjust their business or collapse. [..] The role of policymakers and regulators is ultimately to stimulate competition' ([73], p. 387). If the stranding of assets is the start of a pattern of disruption governments and investors need to establish an asset stranding policy [73] preferably a gradual approach to minimize risks [70], or even 'a credible commitment to non-compensation' [83] as this is unlikely to be a one-off incident.

Phasing-in strategies found in the literature to deal with stranded fossil fuel assets include the adoption of long-term predictable climate and energy policies [84] and diversification or portfolio reweighting and allocation (e.g. [31,85]). This can be done by adopting long-terms targets and timetables on GHG-emissions, and by providing financial and regulatory incentives to switch current and future investments to a low-carbon pathway [19,36,42], for instance, by giving tax breaks or subsidizing energy-efficient materials or clean energy investments (and by taxing energy-inefficient assets) [40]; energy efficiency or emission standards (e.g. in the automobile or building sectors) [36,86]; disincentivizing fossil fuels (e.g. removing fossil fuel subsidies globally amounting to USD 500–$600 billion annually) (e.g. [87,88]); by putting up moratoria (e.g. for coal or unconventional fossil fuels) [36,88,89]; by introducing carbon taxes (e.g. [36,86,90–92]); and/or by a cap-and-trade mechanism (e.g. [34,92–94]). Recognizing the risk of stranded assets may also result in a complete or partial divestment strategy from fossil fuel assets [81,95]. Section 4.2 examines the implications of some of these strategies further from a first comer-latecomer perspective.

3. Trends in the literature

3.1. Shift from electricity to other energy sectors

The literature review on stranded assets and stranded resources in a diversity of fields reveals five general trends. First, the concept of stranded assets has moved from the electricity sector to related energy sectors like fossil fuels, renewables, nuclear and biofuels (but not yet to hydropower) and recently includes investments made in agricultural or forest resources (see Appendix A, Table A1).

3.2. Broadening definition of stranded assets and resources

Second, the conceptual coverage of stranded assets is expanding from a narrow to a broader definition encompassing all characteristics namely, financial, legislative, technological, market related, environmental and social (see Appendix A, Table A1). Assets (and resources) can become stranded due to changes in regulation, markets, environmental risks, societal norms and technology.

3.3. Linking stranded assets and resources to climate change and other environmental challenges

Third, since 2010 there is a trend towards using the concept of stranded assets with reference to climate change (see Appendix A, Table A1) and linking it to (a) the low-carbon transition (stranded carbon assets) and (future) climate regulations and (b) climate-related stranding in both academic and non-academic literature (e.g. [20,80,87,96,97]) (see Appendix A, Fig. A1) and in the social and environmental sciences (see Appendix A, Fig. A2). A quick quantitative analysis of the keywords (3406) of the articles (319) that mention 'stranded asset(s)' in the Scopus database reveals that the top 5 most mentioned keywords are climate change (98), fossil fuel(s) (72), stranded assets (40), environmental policy (28), and energy policy (27).[3]

Climate change impacts are considered a direct cause of the stranding of assets and resources, such as the impacts of increased weather variability, floods, or droughts on assets and resources in forestry, land use and agriculture (see 3.4) (e.g. [30,98]). Climate change may also indirectly cause infrastructure in coastal (e.g. ports) or other vulnerable regions to become stranded. At the same time, more and more literature recognizes the potential stranding of assets and resources due to future climate change mitigation regulations including, for instance, the shipping sector (due to the long lifetimes of ships and marine infrastructure) [99], or real estate assets (due to regulatory demands on energy performance or vulnerability to environmental disasters) [100,101].

Stranded assets are increasingly linked to fossil fuels as they are typified as 'polluting assets' ([40], p. i), 'environmentally unsustainable assets' ([67], p. 2), and 'unburnable' or 'unusable' fossil fuels ([3], p. 17) because of external constraints [15] like climate regulations creating risks for fossil fuel companies and host countries [20]. The most cited causes for the stranding of fossil fuel assets are: (i) physical (environmental) challenges (e.g. water scarcity or droughts) [102,103]; (ii) changing environmental, climate change or GHG-emissions regulations (e.g. climate change litigation, air pollution regulations or carbon taxes) [42,75,103,104]; (iii) changing market conditions (e.g.

[3] Analysis done with Python using data export on keywords from the Scopus database on 'stranded-asset*' in all fields, excluding irrelevant fields of science (see footnote [2]), resulting in 344 articles and 2,701 keywords.

Table 1
The different aspects of stranded resources and assets.

Aspects	Stranded Resource	Asset	Stranded Asset	Liability
Spatial	When the resource is remote/inaccessible (e.g. gas or renewables too far from users)	When place is not an issue and the resource can be exploited	When a changing resource landscape affects the access to the asset (depletion of resources; water scarcity)	When the investor has to pay clean-up costs for emergencies with a specific spatial aspect
Technological	When technologies are not available (e.g. deep-sea mining technologies)	When technologies are available (e.g. for hydraulic fracturing or hydrogen technologies)	When new technologies make old ones obsolete (through standard ratcheting and disruptive innovation)	When companies are held liable for dangerous/obsolete technologies
Economic	When there is no market for a resource or when it is uneconomic to extract/convert	When viable projects lead to investment (e.g. in biofuel plantations through deforestation)	When markets or increased competition affect the asset (e.g. falling oil prices affected Shell's Arctic investment)	When companies or governments have to pay for the premature stranding of assets (e.g. decommissioning costs or unemployment costs) or when the state must compensate companies for phase-outs (e.g. nuclear phase-out in Germany)
Ecological	When ecological impacts are used as arguments for non-use (e.g. with large hydro dams)	When economic gains outweigh ecological impacts	When ecological arguments outweigh economic arguments; or when natural disasters (e.g. in Fukushima) or the impacts of climate change (e.g. agricultural assets) affect assets	When injunctive relief is accompanied by punitive damages. When the investor is left with the costs of adaptation or the need to insure against such risks
Political	When political circumstances do not allow for exploitation (e.g. in situations of civil war)	When political choices/situation allow for exploitation	When (geo-)politics affects assets (e.g. sanctions on Iraq affected Chinese oil/gas contracts)	When governments or organizations are held liable for (short-term) policies (e.g. aid agencies for export credits on polluting industries)
Legal/Policy	When laws restrict extraction or conversion (e.g. moratoria; National Parks; forest protection laws; standards)	When laws permit use, contracts, leases, and intellectual property rights/patents	When new legal norms retire an asset or make it unusable (e.g. phasing out nuclear; climate change litigation; laws emerging from the circular economy)	When newer laws or climate litigation impose liability for clean-up after mining or compensation for damages on humans and the environment (e.g. first-generation biofuels); or when governments are held accountable for the premature stranding of contracts/investments due to policy changes under trade agreements protecting investor rights
Social	When consumers or communities prevent use (e.g. ban on oil exploration in Lofoten, Norway; local fracking bans)	When consumers or communities want to benefit from resource use	When consumers or communities successfully object to extractive industries (e.g. Keystone pipeline XL protests)	When the communities demand compensation for damages (e.g. because of damages to buildings in Groningen or from oil spills Nigeria)

falling demand, cost-competitiveness of renewables) [103–106]; (iv) technological changes (e.g. falling renewable or clean technology costs) [107,36]; and (v) changing social norms (e.g. consumer behavior preferring clean energy or some resources and assets – typically unconventional fossil fuels – becoming socially unacceptable) [103,108,109].

Among changes in regulation is the growing litigation risk faced by fossil fuel companies [103] as climate change litigation is on the rise and courts have 'tended to enhance, rather than hinder, climate regulation' ([110], p. 17; [111,112]). Court cases – such as Urgenda's case urging the Dutch government to cut GHG-emissions at a faster pace – are pushing for more stringent domestic climate change mitigation policies (thereby possibly stranding coal power plants prematurely). Other cases focus on particular (carbon) projects, such as the successful claim of Earthlife Johannesburg over the need to consider climate change impacts when permitting new coal-fired power stations. As the causes of stranded fossil fuel assets are manifold, they all emphasize the need to phase out fossil fuels. Added to this is the risk of creating or aggravating carbon lock-in effects of the economy (see 2.5) exacerbating the stranded asset risk with possible future liabilities [113].

3.4. Recent coverage of agricultural assets and forests as stranded resources

Fourth, the literature generally deals with fuel or generating resources. Only recently has the concept of stranded resources been linked to forestry, agriculture and other land-uses (e.g. [42]).

As forests become protected, they are turned into stranded resources that cannot be 'developed' [64]. Forests previously designated for biofuel production are recognized as potential stranded resources [64], just like land leased to palm oil concessions under buyer's anti-deforestation policies [114]. The same is true for other agricultural commodities which are strong drivers of deforestation (and carbon emissions) and therefore prone to stranding, such as beef, cocoa, soy or agricultural resources in regions where production is affected by climate impacts [98]. As with carbon assets (see 2.5), the stranding of forests or agricultural resources and assets will have cascading effects on, among others, land and infrastructure owners, and any upstream or downstream producers or users of 'unsustainable forest' goods [98].

A mechanism that deals with the costs of stranded forest resources is the REDD programme (see 2.5) urging developing countries to reduce their negative impact on forests. REDD recognizes that countries should be able to use their forest lands for other purposes and if they cannot they may need to be compensated for the lost opportunity costs (e.g. profits related to the usage of forestland for biofuel production). The forest transition theory shows that past transitions patterns follow a period during which forests are untouched, then forests are cut down to enable subsistence farming, then deforestation accelerates to enable advancing agricultural economies, and finally forests are maintained when societies become rich enough to prioritize their forests [115–117]. This implies that asking countries to stop deforestation irrespective of their development status puts a very high cost on latecomers to development [118]. REDD aims to compensate developing countries for protecting their forests from deforestation and forest degradation. Since the Bali Action plan in 2007 [118] voluntary REDD readiness programmes funded by donors have started, but the mechanism still has to be fully operationalized [119]. If compensation commitments under REDD are not forthcoming, this may mean that the institutions developed (e.g. to make countries REDD-ready) may be at risk of stranding as well.

Although the literature on REDD does not explicitly recognize 'stranded forests' it does present a potential mechanism for dealing with the stranded assets issue from a first comer-latecomer perspective: compensating for the opportunity costs of not developing a resource (stranded resource). The characterization of forests as stranded resources does not imply that we are in favor of deforestation, merely that we acknowledge its impacts on latecomers.

3.5. The linking of stranded assets to stranded resources

Fifth, there is an emerging trend of linking stranded assets to stranded resources (e.g. [120]). Since the concept of stranded assets has expanded to cover multiple energy sources (see 3.1), both concepts are increasingly used with reference to one another. The stranded resources literature is slowly covering the implications of environmental impacts on the stranding of resources (see Appendix A, Table A2).

We argue that the distinction made between stranded assets and stranded resources is justified by stranded renewable energy resources (i.e. natural endowments) that do not have to be converted into assets before they can become stranded such as the potential energy from the sun, water or wind. From the literature we have developed a matrix (Table 1) on stranded assets and resources that both differentiates and connects stranded assets and stranded resources. Table 1 has seven dimensions and encapsulates the lessons learnt from the examples described above. We define resources as including land, water, minerals and metals, ecosystem capital and services. Row 1 shows the reasons why resources are stranded, when resources become assets, and when they can turn into stranded assets with the risk of liability. Column 1 presents seven aspects of the stranded resources/assets issue – spatial, legal/policy, economic, technological, political, social and ecological.

4. Analysis of global sustainable development issues

4.1. First comer-latecomer dimensions of stranded assets and resources

The literature review and the identified trends lead us to conclude that stranded assets may imply huge costs for investors and for those upstream and downstream of the production chain, and eventually the whole economy. They may attempt to pass on these costs to consumers or demand compensation from the government for their losses. In this section we assess the implications of stranded resources and stranded assets for latecomers to development by building on the aspects described above (cf. Table 1).

Most of the literature focuses on the risks for fossil fuel investors and how they are reevaluating and adjusting their portfolio allocation, and scarcely deals with first comer-latecomer aspects: the consequences of stranded resources and assets for the latecomers to development or on questions of equity inherent to this issue. By definition, first comers exploit their resources and assets first and may become rich as a consequence. Latecomers can benefit by learning from the mistakes of the first comers. However, such learning processes are not without challenges. Derived from the different aspects in Table 1 we develop a first comer-latecomer perspective related to stranded assets and stranded resources which shows us that there are, at least, seven important first comer-latecomer dimensions that are only beginning to be covered in the stranded resources/ assets literature (see Table 2): cf. (i) spatial (see 4.1.1); (ii) technological (see 4.1.2); (iii) economic (see 4.1.3); (iv) ecological (see 4.1.4); (v) political (see 4.1.5); (vi) legal (see 4.1.6); and (vii) social (see 4.1.7).

4.1.1. The spatial dimension: development space

First, from a spatial perspective, first comers first use their own resources (or protect their own resources) and then the resources of other countries for their own development; they often use these resources beyond tipping points leaving little environmental utilization space for latecomers to develop. The economic growth of developed countries has been largely based on unrestricted fossil fuel use and corresponding global emissions. The concept of 'the ecological footprint' (or use of the world's biocapacity) shows how industrialized countries are taking more than 'their share' of the Earth's resources. The carbon footprint of most industrialized nations is generally higher than the footprints of developing countries; and the footprint of industrialized countries spatially spreads out over other countries (cf. 4.1.2) [104,121,122]. Historically, developed countries have a larger responsibility for the global temperature rise [123]. And analysis of historic resource flows from 1962 to 2005 shows that industrialized countries (excluding Canada and Australia) are net importers and developing countries and transition economies are net exporters of resources (with oil as the most important commodity) [124]. This means that latecomers may face obstacles to development either because resources are increasingly exhausted and hence more expensive; because the carrying capacity of the Earth limits their use of resources; or because biodiversity protection requires them to reduce their use of resources. Furthermore, as many oil and gas producing countries lacked the capital or technology to increase resource production themselves foreign multinational oil companies took the lead [125]; and as much of the easy oil and gas is already exploited, latecomers, such as China, tend to invest in more risky or relatively more unprofitable fossil fuel resources (e.g. in Iran or Kazakhstan) (e.g. [125,126]).

4.1.2. The technological dimension: technology dumping and carbon leakage

Second, from a technological perspective, first comers transfer (or postpone) stranded technological assets from their countries and industries to latecomers through technology dumping availing weaker laws and standards in these countries or through their own aid and trade policies; this is not covered in the stranded assets literature but more in the development studies literature (e.g. [127–129]). The extensive literature on technology transfer and dumping shows how Western technologies moved to latecomers when they were phased out for whatever reason in the developed world. This has happened for example in the case of ozone depleting substances (ODS) – where soon after the adoption of the Vienna Convention on the Ozone Layer in 1985 [130] ODS production facilities moved to the developing world (e.g. [131]); the subsequent Montreal Protocol of 1990 gave developing countries extra time to phase out these facilities – which would not been necessary if such facilities had not moved to the developing countries in the first place. Another example is the use of lead paint – causing environmental damage and serious health problems – which is restricted in most developed countries but is allowed in some developing countries [132] and is still sold by Western multinationals [133,134].

This issue of dumping is related to the 'carbon loophole' or 'carbon leakage' idea that describe the trend of displacing carbon intensive industries or technologies to countries with laxer environmental policies, generally developing countries [90,135,136]. Through the outsourcing of carbon-intensive production – designated for industrialized (consumer) markets [136] – the share of GHGs is dropping in industrialized countries, while in developing and emerging countries this share is growing [137]. Increasingly, emerging economies like China are relocating some carbon-intensive production (e.g. the production of raw materials) to developing countries [136]. This also means that effective global emission reduction may be undermined as the Paris Agreement mainly advocates unilateral climate policy and relies on a global review of efforts with no legally binding enforcement mechanisms.

At the same time national Western aid and trade agencies support the transfer of carbon-intensive technologies to developing countries. Recent research has shown that aid agencies in Germany, the UK and USA actually support domestic industry to export knowledge and knowhow on the extraction of fossil fuels to developing countries, including India, under the argument that the poor need to have access to these resources while simultaneously easing the pain of national stranded assets (technologies, knowledge, labor) in their own jurisdictions [138,139]. Besides, G7 countries continue to provide governmental support for the production and use of fossil fuels (amounting to at least 100 billion U.S. dollars annually), both at home and abroad, with developing countries as main recipients (either middle income or low-income countries) [140]. This means that the burden of climate change mitigation is passed onto developing countries, increasing the risk of carbon lock-in for latecomers.

Table 2
Seven first comer-latecomer dimensions of stranded resources and assets.

Aspects	Types	Explanation
Spatial	Development space used	When first comers use their own resources and then the resources of other countries for their own development, or when they preserve their own resources and first use the resources of others leaving little environmental utilization space for latecomers to develop and use their resources (cf. the ecological footprint of nations)
Technological	Leakage 1	When first comers postpone the costs of stranded assets by dumping the technological asset on the latecomer (leakage - 1): for example, transferring carbon-intensive ozone depleting substance related technologies from first comers to latecomers
Economic	Compensation, Leakage 2	When latecomers demand compensation for problems caused by first comers (e.g. for adaptation to the impacts of climate change/ referred to as 'loss and damage' discussions in the climate negotiations) or for the opportunity cost of stranding the resource (e.g. the Yasuni-ITT initiative); When first comers postpone the costs of stranded assets by indirectly transferring the economic asset on the latecomer (leakage - 2): for example, when shares in fossil fuel companies are divested by first comer investors and sold to latecomers
Ecological	New knowledge	When first comers can use and benefit from the resource, but latecomers are obliged to desist because of new knowledge on resource use impacts (e.g. forests, first-generation biofuels, dams, biodiversity protection)
Political	Arguments	When first comers *and* latecomers use the argument that the other is using problematic resources and assets as an excuse for inaction (e.g. in climate negotiations)
Legal/Policy	Contracts	When latecomers develop their resources into assets under long-term legally binding international contracts, making it difficult for them to change these contracts without incurring liability and compensation risks (e.g. restricting mining in Panama, Colombia)
Social	Contextual	When groups within latecomer countries have different visions on development (e.g. Buen Vivir; Ubuntu, Ecological Swaraj) that need to compete with the ideas on development of first comers (e.g. neo-liberal approaches)

4.1.3. The economic dimension: compensation and leakage of fossil fuel shares

Third, from an economic perspective, although the literature review reveals that paying compensation for the stranding of assets (opportunity costs foregone) can enable a national phase-out (see 2.5), latecomers to development will unlikely be compensated for not developing through fossil fuels. While compensation for maintaining forests is being institutionalized, it is not clear if this is a sustainable solution or a red herring [141]. Based on equity principles some advocate for the adoption of a compensation scheme to deal with stranded fossil fuel assets in developing countries (e.g. [142–145]). However, compensation for not using oil is extremely unlikely. While OPEC countries have been trying to negotiate this since 1992, this is clearly not acceptable to the industrialized countries. We believe compensation schemes for leaving fossil fuels underground would be inefficient and unrealistic given: (a) the prospects of large financial demands [146,147] as many countries and companies would most likely want (close to) the equivalent of the opportunity costs of not developing the resources [65]; (b) the duration of compensating could create issues (i.e. countries could lift the moratorium again in the future) [65,91]; (c) there may be dependency concerns for developing countries [65]; (d) while compensation would not alter demand and would displace extraction (cf. the issue of leakage) [91,148]; and (e) countries may more aggressively seek new fossil fuel resources to obtain compensation [148] thereby intensifying the stranded assets problem.

At this time the global community already lacks sufficient and continued funding for the Green Climate Fund [149] and despite the development of the REDD mechanism, there is a clear lack of motivation and resources to ensure that this becomes a viable long-term strategy to protect forests (cf. [119]). Besides, the failure of the Yasuni-ITT initiative – an initiative supported by the Ecuadorian government asking international compensation for leaving oil resources underneath the biodiverse Yasuni National Park underground – shows that internationally compensating countries for stranded fossil fuel assets may be practically unachievable [150]. With Yasuni-ITT European countries were reluctant to compensate countries for leaving fossil fuels underground, although they argued that they would be willing to pay to protect biodiversity [151]. The prospects of large financial demands from other countries was one of the reasons the initiative eventually failed [146,147]. An additional economic risk is the potential compensation claims of latecomers for adaptation costs or losses caused by climate change [152,153].

Another potential – not yet studied issue of leakage – may occur through the divestment of shares in fossil fuel companies. While divestment from fossil fuel assets has been advocated by some environmentalists, such as the Fossil Free movement [154], the mere act of divesting may not (yet) alter the actual amount or price of fossil fuel shares in the market as profit-seeking investors may still buy these shares (cf. [155]). The question is, if Western actors are divesting from fossil fuels, who is then buying these shares? If it is the latecomer – indifferent to the risks attached to these shares – they will be the ones stuck with stranded assets. Currently, the fossil fuel divestment movement is predominantly effective in first comer countries [156]. Besides, in some developing countries the stranded assets issue may not yet be perceived as a real risk (cf. [93]) especially as the US is clearly giving the impression that it is not in a hurry to address the climate change problem.

4.1.4. The ecological dimension: prevention of use based on new knowledge

Fourth, from an ecological perspective, new knowledge on the cumulative negative global impacts of resources from first comers may prevent latecomers from using their resources/ or may accelerate the rate at which their assets become stranded (e.g. water flows or forests, see 3.4). While on the one hand, it is important for latecomers to leapfrog ahead using the latest science, on the other hand, this is challenging as options for increasing income and wealth may be foreclosed by such science. For instance, first-generation biofuel assets risk stranding due to changes in regulations and socio-environmental impacts [98]; or large hydroelectric assets and the potential energy in water resources risk becoming stranded due to environmental and ecological impacts and risks [157]. This is the same for fossil fuels: rich countries used fossil fuels in the past and now, with accelerating knowledge on climate change impacts, for latecomers a fossil-fuel based development model may no longer be viable.

4.1.5. The political dimension: arguments in climate negotiations

Fifth, from a political perspective, first comers may refuse to take environmental action claiming that latecomers are not doing so; while latecomers may claim that first comers should act first. First comers use the argument that the developing world uses problematic resources and assets, partly as an excuse for not acting to strand resources and assets within their own territories. These arguments are commonly used in climate negotiations (e.g. [152,158]); and this argument has led the US and Canada to not adopt any legally binding quantitative emission reduction targets on greenhouse gas emissions for the period 1990–2020 under the Kyoto Protocol [159]. The 1992 Climate Convention explicitly stated that: (i) as the largest share of historical and current global emissions originated in developed countries, (ii) and developing countries are particularly vulnerable to climate impacts and need to prioritize poverty eradication and economic growth, (iii) in accordance with their common but differentiated responsibilities and respective capabilities developed countries need to take the lead in mitigating emissions and

(iv) provide financial and technological resources and assistance to developing countries [11]. Due to, among others, global economies of scale low carbon and renewable energy alternatives are becoming increasingly affordable or even cost-competitive with fossil fuel technologies; they do, however, generally require higher up-front investments than fossil fuel technologies [85]. Climate finance could assist developing countries in fulfilling their mitigation obligations and supporting low carbon development [160]. Yet, promised technological and financial transfers from industrialized countries have scarcely materialized [112,160]. At the same time, developing countries use the argument that industrialized countries are responsible for creating the climate problem, and are not mitigating fast enough or assisting developing countries in adaptation and mitigation efforts, as a justification for not stranding their own fossil fuel resources and assets (cf. [152,161,162]).

4.1.6. The legal dimension: liability issues for latecomers

Sixth, from a legal perspective, investments in resources and assets in a globalizing world often involve long-term contracts protected under private (international) law and may cause policy freezing and liabilities in latecomers. If investments in developing countries are made through long-term legally binding contracts under international investment and contract law, this may complicate phasing out such contracts without having to compensate the investor (cf. [163]). States are being sued under international law (i.e. bilateral or multilateral agreements) through, inter alia, international investor-state dispute settlement (ISDS) mechanisms – for adopting environmental or climate change policies that impact fossil fuel investors' profits. For instance, Panama is being sued by U.S. mining company Dominion Minerals under a bilateral agreement over the rejection to extend their terms of concession rights in mining, the company now claiming USD 268.3 million for its loss of investments [164]; and under a Free Trade Agreement Canadian Eco Oro Minerals is suing the Columbian government over the deprivation of the company's mining rights [165]. Notably, the majority of ISDS claims have been brought up by Western investors against developing countries and transition economies [166,167].

The Energy Charter Treaty (ECT) – a legally binding agreement, applicable to the UN ECE countries and now open for international participation – has established a framework for cross-border cooperation in the energy industry. The ECT provides certainty to investors through mechanisms for dispute settlement and has triggered the most investor-state law claims in recent times [166]. Until now, the majority of claims (61%) have been settled in favor of the foreign investor [168]. Protected by the ECT, carbon-dependent companies are claiming compensation for a change in environmental policies and for government policies limiting fossil fuel extraction. For instance, oil and gas multinational Rockhopper is suing Italy for banning offshore oil drilling in the Adriatic Sea out of fear of environmental damage and earthquakes [166,168]; the company claims compensation for stranded exploration investments (USD 40–50 Million) as well as compensation for future forgone profits (USD 200–300 Million) [166]. Quebec's government has been sued by American oil and gas exploration company Lone Pipe Resources for denying hydraulic fracturing (or 'fracking') under the Saint Lawrence River claiming over USD 100 Million [166]. And in the case of Germany's nuclear phase-out (see 2.5), Swedish nuclear power utility Vattenfall filed an additional lawsuit at the ICSID asking for almost EUR 4.7 billion compensation [169].

These examples show how investment treaties are curtailing progressive environmental and climate change policy implementation. Even the threat of these multifigure compensation claims may discourage countries from phasing out fossil fuels [168]. Some countries are withdrawing from the ECT (e.g. Russia and Italy); at the same time several developing countries are planning to join the ETC (e.g. Burundi, Bangladesh, Colombia, Kenya, Uganda, Guatemala) [166,168]. These countries need to be sensible and know the risks they may be facing, especially given the often weaker position of developing countries [168] and the amount of compensation claimed [170]. This is important for developing countries like, for example, Kenya, where oil exploration and production activities are mainly in the hands of international oil companies [93]. The outcome of these court cases is unknown at the time of writing this article. A favourable outcome for the investors could imply that foreign companies can successfully demand large compensation sums under international investment protection regulations for (future) stranded assets. Another example of potentially problematic bilateral contracts are the long-term oil supply contracts between Chinese and Latin American oil companies and governments, which could limit future transitions [171]. For developing countries, it will be important to rethink joining treaties with ISDS mechanisms or to renegotiate these treaties to exclude environmental or climate related policy changes from investment clauses.

4.1.7. The social dimension: contrasting notions of development

And lastly, seventh, from a social perspective, latecomers may adopt different visions on development than first comers. Although not fully discussed in this paper, in some developing countries contrasting thoughts on development and related natural resource management emerge. New understandings can be found in the emergence of 'Buen Vivir' in South America [172], the 'Ubuntu' philosophy in Sub-Saharan Africa [173], or the ideas on 'Ecological Swaraj' ('radical ecological democracy') in India [174]. Social opposition against environmentally problematic resources has led some countries to restrict mining or extraction, such as restrictions on industrial metallic mining in El Salvador [175], bans on hydraulic fracking in Uruguay [176], local regulations against fracking in Argentina [177], or the nationwide oil exploration and extraction moratorium in Costa Rica (Kane, 2014).

4.2. Strategies in dealing with stranded assets and resources in the context of global sustainable development

The above demonstrates that the stranded assets issue is important for the future of global sustainable development. With regard to fossil fuels the issue can seriously affect prospective investors in oil and gas such as Kenya or Mozambique. Should they invest in these resources since industrialized countries continue to use fossil fuels a quarter-century after the Climate Convention of 1992 and despite the Paris Agreement? Or do they run the risk that these assets will become stranded in the next few decades as the Paris Agreement increasingly is implemented? And if a large part of the world's fossil fuel resources is to become stranded in a 1.5-2 °C scenario, who should be able to use the remainder of the fossil fuels? Many rich countries have used fossil fuels to industrialize their economies and latecomers think it is their turn under the Right to Development [93] and the Right to Sustainable Development [10]. And equitably sharing the remaining carbon budget on the basis of, for instance, historical responsibility of GHG emissions, human development indexes, availability of other sources of energy or wealth (cf. [142]), or on the basis of the conservational value of reserves (cf. [144]), will only create new stranded assets in developing countries (cf. the long lifetimes of fossil fuel plants and related infrastructure) [60,65].

Developing a fossil fuel sector in prospective fossil fuel producing developing countries will compromise the long-term development of these countries by locking them into unsustainable pathways. Many low-income countries already are largely dependent on fossil fuels and need resources for development [178]. Most of the coal and oil capacity in non-OECD countries has been deployed within the last two decades (cf. in OECD countries oil and coal deployment peaked around the 70 s–80 s), meaning that these countries are left with newer assets; at the same time non-OECD countries can least afford the potential loss of value of these assets due to their lower levels of economic development [179]. Latecomers dependent on fossil fuel extraction may also be worse off in the long term when prices decline causing a decrease in domestic earnings, impacting growth and potentially endangering political and social stability [137].

Strategies, cited in the literature (see 2.5), to deal with stranded assets in the context of fossil fuels and climate change mitigation can be broadly categorized into: (a) phasing-out strategies (full or partial compensation, including grandfathering) (see 4.2.1); or (b) phasing-in strategies (i.e. incentivizing low-carbon (technology) development) (see 0). Now, let us unpack these two different pathways and see what they entail for latecomers to development in the context of global sustainable development (see 4.2.3).

4.2.1. Phasing out strategies

In the international context, states may be forced to compensate multinationals when investments were made under multilateral or bilateral contracts with investor-state arbitration. Within the national context, fossil fuel investors may claim compensation from the national government for the premature stranding of their assets. The state is unlikely to fully compensate domestic industries for closure – because production processes and knowledge are continuously evolving and it is the industry's responsibility to continuously modernize or face the risks of market changes (i.e. the process of creative destruction); they, however, may recover stranded assets partially (cf. as in the German case, see 2.5). In the Netherlands, social protests in Groningen, resulting from increased earthquake activity and related damages to homes and buildings, has led the Dutch Government to phase out natural gas extraction in Groningen. Given current gas prices, the 450 billion cubic metres (m^3) of stranded gas in this field amounts to around Euro 70 billion in stranded assets [180]. In return for this write-down, a larger percentage of the damage that will be paid to the affected house owners will be borne by the state, while at the same time the state's share in gas profits is reduced (annually (below) 12 billion m^3 will be extracted) [180].

This form of partial compensation or grandfathering – a way of gradually phasing out and supporting (potential) losers of the transition – can be employed to smoothen the transition [90]. But slow phasing-out policies – exempting carbon intensive industries from new rules – may at the same time sustain lock-in problems as the market becomes distorted and investments are not pushed towards low carbon technologies [70]. Besides, one could argue that those with stranded investments in the fossil fuel sector did not invest without prior knowledge that these assets may be stranded before the end of their useful life. Even within the fossil fuel sector, large multinationals have been aware of the relation between fossil fuels and global warming for quite some time; in fact, they even advertised their knowledge about climate change.[4]

4.2.2. Phasing-in strategies

As opposed to phasing out, policies could also be directed at phasing-in more sustainable technologies to foster the transition. Phasing-in would mean reducing investment uncertainty and directing investments towards low-carbon resources and innovation with the adoption of long-term stable and clear climate mitigation and energy related regulations. Policies would focus on decarbonisation [42] and diversification of the economy to decrease the dependency on fossil fuels, avoid (further) carbon lock-in effects (cf. portfolio re-weighting and diversification, see 2.5) [74,81,113] and could consider the various options (see 2.5) (e.g. carbon taxes, clean investment subsidies, energy efficiency standards etc.). For decarbonisation to take off low- to no-carbon technologies need to become either cheaper or outperform carbon-intensive technologies [91]. This could mean redirecting research and development budgets – public and private – to the low- to no-carbon transition (e.g. in alternative energy resources, battery life-extension etc.) [88].

Acting early includes important co-benefits, such as the avoided costs of climate damages and health impacts, improved air quality, more efficient energy use, more resilient energy systems, and increased food security and water availability [181,22,137]. Investing in renewable energy resources will be more rewarding in the long run than investing in fossil fuels [65] and transiting to a green economy will create more new job opportunities, offsetting stranded jobs in carbon-intensive sectors [182]. This implies that latecomers need to try to avoid (new) stranded assets, leapfrog carbon-intensive development (escape lock-in mechanisms) and pursue a more sustainable development path using modern technologies.

Yet, for many latecomers a diversification strategy or a low-carbon development path is only attainable with financial and technology transfers from industrialized countries. The same is true for new fossil fuel producing developing countries: only if credible and sufficient technology and capital transfers from first comers to latecomers materialize these countries could afford leaving their fossil fuel resources underground as they need income and energy to spur development and meet rising energy demands (e.g. [65,93]). This may also be the only option that addresses both economic efficiency (i.e. avoiding new stranded assets and carbon lock-in) and equity issues (i.e. addressing the Right to Development of countries) while sharing the carbon budget in the most optimal way through emission allocation based on equity concerns [93,94].

4.2.3. Limitations to both strategies

From a global sustainable development perspective both phasing-in and phasing out policies may also prove to be counterproductive. The stranded assets issue works under the assumption that the world is becoming increasingly hostile to carbon-intensive energy resources and that future regulations will restrict the use of fossil fuels. It also works under the assumption that the Paris Agreement will be implemented (cf. [65]). Some criticize this assumption by arguing that a real low-carbon transition may take several decades; fossil fuel investors mainly look at short-term profits and investment horizons; fossil fuel companies are among the world's largest companies by total revenue (e.g. Sinopec, Shell and Exxon Mobil) [183]; and any decline in fossil fuel prices may make fossil fuels more competitive [184]. This argument relates to 'the Green Paradox' which assumes that future climate and GHG-emission regulation policies (e.g. carbon caps or taxes) could ignite a 'race to the bottom' of the remaining fossil fuel reserves to sell as much fossil fuels before new restrictions are enacted (e.g. [185]). Consequently, a period of over-supply (paired with declining demand) coupled with low prices could ignite price wars and incentivize fossil fuel producers to extract at an even faster pace (e.g. [74,76,186]) or would cause leakage as declining prices could stimulate demand for fossil fuels in the developing world [135]. This is not an inconceivable scenario: shortly after the adoption of the Paris Agreement in 2015, Royal Dutch Shell's CEO Ben van Beurden said: 'I will pump up everything to meet the demand' (freely translated, [187]). Needless to say, the world would lose in this race to the bottom.

This means that including the supply side of fossil fuels is critical in both strategies: such as, obliging the fossil industry to compensate with investments in renewables or clean energy; penalizing fossil fuel companies heavily engaged in exploration activities; or sharing the remaining carbon budget by including restrictions or quotas on the production side (cf. [74]). Adding to this is the need to include all sectors and industries in policymaking, such as air transport and shipping. Rockström et al. [88], for example, propose a global 'carbon law', applicable to both countries and industries, aiming to halve CO_2 emissions every decade, stimulating renewable and low-carbon technologies while pushing fossil fuels out of the market. The issue of carbon leakage could be addressed, for instance, by holding industrialized governments accountable for the emissions embodied in imported goods designated for their citizens, such as border carbon adjustments (import tariffs and export subsidies directed to 'designation-based carbon pricing'), 'embodied carbon tariffs' or other trade restrictions (e.g. [92,135]). These tariffs could incentivize

[4] In a 1982 speech Exxon Research' president Dr. E.E. David Jr. stated: '[f]ew people doubt that the world has entered an energy transition away from dependence upon fossil fuels and toward some mix of renewable resources that will not pose problems of CO_2 accumulation' [190]. And in 'Climate of Concern', an education film produced as far back as 1991, Shell reaffirms the scientific consensus on the link between fossil fuels and the increase of CO_2 in the atmosphere with corresponding climate impacts [191].

manufacturers to adopt less carbon-intensive techniques. And as expectations on future energy pathways are critical, it is important that the path to a low-carbon future is credible and clear (both in the policy discourse and policy documents) [83] reducing policy uncertainty [69].

5. Conclusion

In the wake of the Paris Agreement on climate change and the need to restructure the global economy, we have examined the literature on stranded resources and stranded assets – complemented by an analysis of different examples of stranded assets and resources – to gather insights into the implications of the literature on first comer-latecomer issues with regard to climate change.

The literature review on stranded assets and stranded resources in various fields reveals that (see 3): (i) the concept of stranded assets has moved from the electricity sector to other energy sectors; (ii) the conceptual coverage of both stranded assets and stranded resources has expanded; (iii) the concepts are increasingly linked to climate change and other environmental challenges; (iv) the literature, only recently, covers stranded agricultural and forests resources and assets; and (v) the concepts of stranded assets and stranded resources are increasingly linked to each other. We show how spatial, technological, economical, ecological, political, legal/policy and social factors influence the process by which stranded resources can become usable resources and how they can become assets and then stranded assets (Table 1). And we address the various cited strategies for dealing with stranded assets and resources (2.5).

We then applied this more general knowledge from the stranded assets/ resources literature to first comers and latecomers to development. For the latecomers to development, who are per definition at disadvantage in comparison to first comers, the problem of stranded resources and stranded assets will be an enduring challenge in the future. We identified seven dimensions (Table 2) in line with the various aspects of stranded assets and resources (Table 1): (i) spatial: where first comers use their own resources and then the resources of other countries for their own development leaving little environmental utilization space for latecomers to develop; (ii) technological: when first comers dump older technologies (stranded assets) on latecomers through aid and trade strategies; (iii) economic: when first comers may avoid paying compensation for damage or for the stranded resources and assets of latecomers; and may potentially also indirectly transfer worthless shares to latecomers; (iv) ecological: when new knowledge from first comers on the cumulative negative impact of resources may prevent latecomers from using their resources/ or may accelerate the rate which their assets become stranded; (v) political: when first comers may refuse to take environmental action claiming that latecomers are not doing so; while latecomers may claim that first comers should take action first; (vi) legal/policy: when investments in resources and assets in a globalizing world involve long-term contracts protected under private law that may cause policy freezing and liabilities in latecomers; and (vii) social: when latecomers may develop new and different visions on development than first comers.

Although stranded assets are inherent to competitive markets; focusing on phasing out or grandfathering latecomers may only lead to (further) lock-in mechanisms inflicting cascading effects on the whole economy and hampering sustainable development in the long run. Besides developing countries run the risk of having to pay compensation under investor law with ISDS mechanisms. Latecomers thus need to be sensible in deciding which sectors to develop, focus on phasing-in low- to no-carbon technologies (leapfrogging carbon-intensive development) and avoid creating new stranded assets as a fossil fuel development model will be too risky, but they need to move fast as any delay in action will only increase the amount of stranded assets.

Sharing the remaining carbon budget in both an economically effective and equitable manner through allocating country-specific extraction caps might be a solution to prevent the world's temperatures to rise above the critical 1.5–2 °C limit while adhering to the Right to Development of countries. Without concerted global action individual fossil fuel producers might just try to pump up as much as they can and wherever they can in the short term. The global community has a role to play in guaranteeing cooperation to avoid the green paradox, addressing the issue of carbon leakage, and ensuring that developing countries can pursue a sustainable development path.

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Appendix A

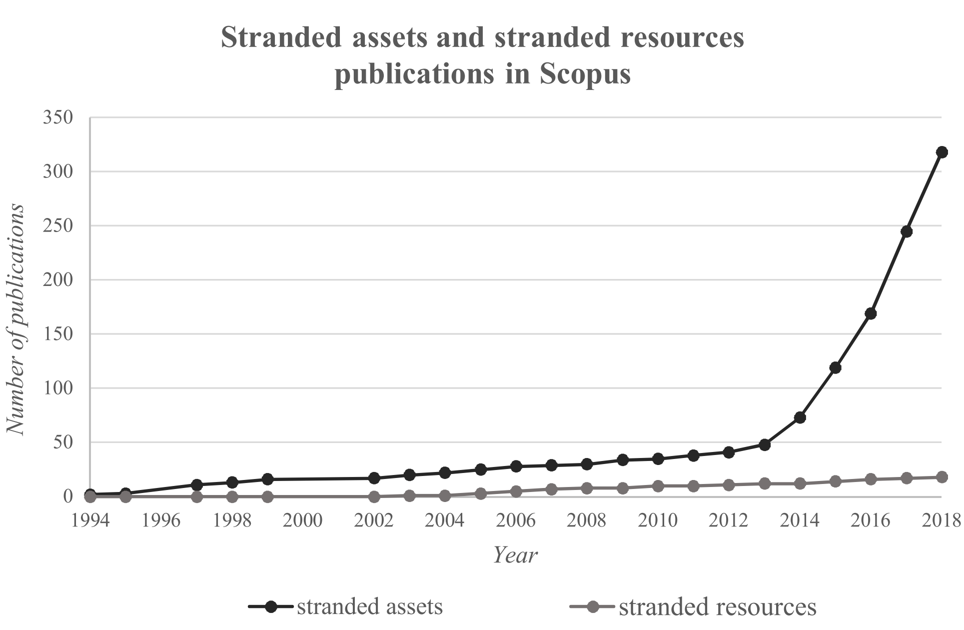

Fig. A1. Time-line of stranded assets and stranded resources publications in Scopus (1994-October 2018). Source: self-generated from Scopus' data.[1]

[1]Searched for 'stranded-asset*'/'stranded-resource*' in all fields in Scopus, excluding chemistry, mathematics, biology, medicine, computer science, physics and astronomy, and arts and humanity. The stranded assets' literature shows 319 publications, the stranded resources' literature shows 18 publications.

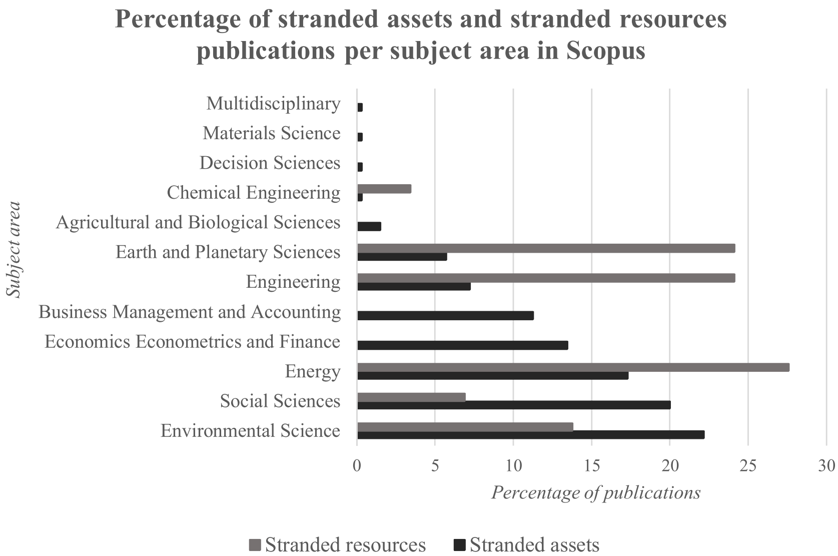

Fig. A2. Subject distribution of stranded assets and stranded resources publications in Scopus (1994-October 2018). Source: self-generated from Scopus' data.[1]

[1]Searched for 'stranded-asset*'/'stranded-resource*' in all fields in Scopus, excluding chemistry, mathematics, biology, medicine, computer science, physics and astronomy, and arts and humanity. The stranded assets' literature shows 319 publications, the stranded resources' literature shows 18 publications. N.B. articles can be categorized in more than one subject area.

Table A1
Example of a concept matrix of papers applying stranded assets to different sectors for different reasons.

Author(s)	Sector	Reasons					
		Financial	Legislative	Technological	Market	Environmental	Social
Blumstein and Bushnell [38]	Electricity	x					
Price and Kristner [39]	Electricity		x				
Crew and Kleindorfer [29]	Network industries	x	x				
Babiker et al. [34]	Carbon intensive sectors		x				
Mariyappan and Anderson [194]	Renewable energy		x				
Lutzenhiser [68]	Fossil fuels				x		
Parker and Oczkowski [195]	Water	x					
Thomas [196]	Nuclear		x				
Nuttall and Taylor [72]	Electricity (nuclear)	x	x		x		
Stern [32]	General	x		x	x		
Uibeleisen [35]	Coal-fired plants		x				
Carbon Tracker [3]	Fossil fuels		x		x		
Charles et al. [197]	Biofuels	x					
Ansar et al. [44]	Fossil fuels	x	x	x		x	x
Caldecott et al. [67]	Agriculture	x	x	x	x	x	x
Generation Foundation [8]	Fossil fuels	x	x	x	x	x	x
IEA [16]	Fossil fuels	x	x		x		
Caldecott and McDaniels (2014)	Fossil fuels	x	x	x		x	x
Robins [43]	Fossil fuels	x	x	x		x	x
Fay et al. [41]	Fossil fuels		x	x	x		x
Rautner et al. [98]	Forestry, agriculture, land-use	x	x	x	x	x	
Bos and Gupta [93]	Fossil fuels	x	x	x	x	x	x
Caldecott et al. [42]	Fossil fuels, agriculture, forestry, tourism and indirectly affected sectors[a]	x	x	x	x	x	x
Schlösser et al. [137]	Fossil fuels	x	x		x		
Reddy and Anbumozhi [30]	Agriculture	x	x		x	x	x
Bos and Gupta [65]	Fossil fuels, nuclear	x	x	x	x	x	x
Kefford et al. [179]	Fossil fuel plants						
Gupta and Chu [64]	Fossil fuels	x	x	x	x	x	x
Overseas Development Institute [193]	Coal	x	x	x	x	x	x

[a] E.g., energy-intensive sectors, such as infrastructure, real estate, mining.

Table A2
Example of a concept matrix on stranded resources: authors, applications in different sectors and reasons elaborated.

Author(s):	Stranded resources in different sectors/ fields:	Reasons						
		Spatial/ physical	Technological	Economical/ commercial	Regulatory	Poltical	Environemntal	Social
Moniz and Kenderdine [50]	Natural gas	x	x	x				
Kolian and Sammarco [198]	Natural gas and oil			x				
Roberts [51]	Natural gas	x						
Mayer [199]	Renewables	x						
Dong et al. [55]	Natural gas	x		x		x		
Ball and Wietschel [57]	Renewables	x						
Economides and Wood [49]	Natural gas	x	x	x				
Khalilpour and Karimi [47]	Natural gas	x		x				
Leighty and Holbrook [58]	Renewables	x	x					
Johnson et al. [60]	Renewables	x	x	x				
Attanasi and Freeman [46]	Natural gas	x	x	x				
McGlade et al. [54]	Natural gas			x				
Leather et al. [53]	Natural gas	x	x	x				
Hunter [56]	Oil	x		x				
Nguyen et al. [59]	Biomass	x	x	x				
Desai et al. [48]	Natural Gas	x	x					
Bergbauer and Maerten [52]	Natural gas	x	x					
Speight [61]	Natural gas and oil	x		x				
Gupta et al [192].	Fossil fuels, forests			x	x		x	
Bos and Gupta [65]	Fossil fuels, nuclear	x	x	x	x	x	x	x
Gupta and Chu [64]	Fossil fuels	x	x	x	x	x	x	x

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