Energy for Sustainable Development 73 (2023) 76–86

Contents lists available at ScienceDirect

Energy for Sustainable Development

journal homepage: www.journals.elsevier.com/energy-for-sustainable-development

Review

Stranded assets and sustainable energy transition: A systematic and critical review of incumbents' response

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ARTICLE INFO

Keywords:
Climate change
Energy transitions
Incumbents
Stranded assets
Systematic literature review

ABSTRACT

Climate-related stranded assets have been a popular research topic of many studies over the last decade. Past studies have mostly focused on estimations of stranded assets and mitigation options. While the studies consider energy transitions, the influential factors behind the choice of options have not been investigated in-depth. Because such choices may have path dependency, affecting the direction and speed of subsequent changes, it is critical to understand stranded asset risk and its relations to choices and the transition more comprehensively. To do so, we conduct a systematic literature review to explore the impacts of stranded asset risk on incumbents' decision-making and energy transitions. Our findings demonstrate that stranded asset risk, coupled with transition costs, energy security and sustainability concerns determine the pathway of energy transitions. Higher perceived stranded assets will pave the transition toward a renewable energy-based system, but high concerns about transition costs, energy security, and sustainability would retard the transition or direct the system toward different pathways. Abrupt policy change intensifies regime resistance and energy injustice, but slow change strengthens lock-ins into traditional systems.

Introduction

Climate-related stranded assets have been a popular research topic of many studies over the last decade. This topic is associated with sustainable energy transitions, specifically from fossil fuels to cleaner fuels and technologies, in which efforts to limit the average global temperature to rise well below 2 °C or even further 1.5 °C require significant emissions reduction (Bruckner et al., 2014). In other words, the carbon budget, referring to the cumulative emissions required to stay below the threshold, is indirectly embedded in the amount of fossil fuel combustion that is permitted. Around 34 %–49 % of oil reserves, 49 %–52 % of gas reserves, and 77 %–97 % of coal reserves are predicted to be stranded to achieve the Paris target (IRENA, 2017). This prediction implies fossil-related assets, such as power plants, are exposed to stranded asset risk.

Stranded assets pose significant economic and policy challenges, attracting the attention of policymakers, regulators, companies, investors, and lenders involved in fossil fuel-based energy regimes that counter the deployment of low-carbon technologies (Kefford et al., 2018). A country with a weak climate policy will suffer from large stranded assets to achieve the Paris target (Bertram, Johnson, et al., 2015; Luderer et al., 2016), which can potentially cause adverse economic effects and would be less likely to achieve the long-term climate goals (Oshiro & Fujimori, 2021). This holds particularly for emerging and developing countries with many young coal-fired power plants (IEA, 2021). Strengthening near-term climate policy can reduce or minimize stranded asset risk (IRENA, 2017; Johnson et al., 2015; Malik et al., 2020; Saygin et al., 2019) because early actions can avoid assets from carbon lockins. However, such actions threaten economic prosperity, corporate profits, and existing sociotechnical regimes (Braungardt et al., 2019; Gupta & Chu, 2018; Langley et al., 2021; Ruggiero & Lehkonen, 2017).

Asset stranding is not a novel phenomenon. It aligns with Schumpeter's concept of creative destruction (Caldecott, 2018). According to the most common definition, assets become stranded because of unanticipated or premature write-downs, devaluations, or conversion to liabilities (Caldecott et al., 2013). Factors related to changes in the market, such as economic conditions, technology innovation,

Abbreviations: CFPP, Coal-fired power plant; CCS, Carbon capture and sequestration; CCUS, Carbon capture, use, and storage; SLR, Systematic literature review; WoS, Web of Science.

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https://doi.org/10.1016/j.esd.2023.01.014
Received 20 June 2022; Received in revised form 5 January 2023; Accepted 15 January 2023
Available online 31 January 2023

regulation, financing conditions, and social norms, can instigate asset stranding (Generation Foundation, 2013; Jackson, 2018). Such factors stimulate shifts, resulting in resources being reallocated from one sector to another, people being reskilled and retrained, and capital being depreciated and replaced to smoothen the transformation process, both economically and politically (Zenghelis et al., 2018).

Stranded asset risk is crucial for incumbent actors. As a form of sunk costs, stranded assets work as barriers to both exit and entry due to unrecoverable capital expenditure (Cabral & Ross, 2008; Clark & Wrigley, 1997, 2017; Rennings et al., 2013). Incumbents and investors are less likely to invest when greater uncertainty about the future in decision-making processes increases sunk costs and stranded asset risk (Harnett, 2018).

Stranded asset risk is remarkable in the energy sector. Energy systems are characterized by enormous sunk investments, long operating lifetimes, systemic path dependency, complementary capital investments, and deep embedding in society (Sen & von Schickfus, 2020; Unruh, 2000; Verbong & Loorbach, 2012) and are threatened by the transition to a low-carbon economy, causing asset underutilization and abandonment. Continued investments in coal power plants will contradict the efforts to achieve local, national, and international energy and climate goals, indicating energy policy failure (Sokołowski & Heffron, 2022). Thus, the early retirement of coal-fired power plants (typically used for 30–50 years) is required, and the costs become uneconomical due to a high carbon price (Bertram, Luderer, et al., 2015; Johnson et al., 2015; Malik et al., 2020).

Past studies on climate-related stranded assets primarily focused on estimating the amount of stranded assets with respect to climate policy and mitigation scenarios (e.g., Binsted et al., 2020; Malik et al., 2020; Saygin et al., 2019). Several studies review stranded assets from environmental-related risks (Caldecott, 2018; Shimbar, 2021), climate change and sustainable development (Bos & Gupta, 2019), and investment (Curtin et al., 2019). Others pay attention to mitigation options and influential factors such as energy regime incumbency (Curran, 2020), firm-specific, socioeconomic, and institutional (Mori, 2021), and political, economic, and cognitive power to resist transformative changes and innovation that maintain the status quo and slow down the transition process (Rotmans & Loorbach, 2010). However, they have paid scant attention to the perceived stranded asset risk of incumbents, and policy effects on the transition costs, such as investment costs for expanding renewables, grid, and energy efficiency, despite that both of which may affect energy transition (Unnerstall, 2017).

Against this backdrop, this study reviews the existing research on stranded asset risk to explore how stranded asset risk influences incumbents' decisions to address sustainability transitions and how energy policy influences decarbonization pathways through their perceived risk. This study has two main contributions. First, it provides a comprehensive review that explains stranded asset risk and its relation to the transition to a low-carbon energy system from incumbents' perspectives. Second, it presents a different view for mapping factors influencing possible energy transition options referring to the status quo.

The remainder of this paper proceeds as follows. Methodology section presents the methodology for the systematic literature review. Results section provides the result of the review. Discussion section discusses the speed of decarbonization and policy implications. Finally, Conclusion section concludes the study and provides suggestions for future research.

Methodology

Systematic literature review

A systematic literature review (SLR) is used to review existing research literature in an organized and accountable way, comprising three main activities: (i) identifying and describing the relevant literature, (ii) critically evaluating research reports in a systematic manner, and (iii) synthesizing the findings (Gough et al., 2012). This method is also helpful for researchers to construct a well-structured overview of recent literature in a specific field (Wee & Banister, 2016). This study takes the seven steps for the systematic review proposed by Xiao and Watson (2019): (1) research problem formulation; (2) review protocol development and validation; (3) literature search; (4) screening for inclusion/exclusion; (5) quality assessment of the literature; (6) data extraction; and (7) data analysis and synthesis.

Data collection process

We collected articles from the Scopus and Web of Science (WoS) databases. Previous studies use different terms in discussing "stranded assets," and we refer to Caldecott (2018) to determine the general keywords (e.g., stranded assets, stranded costs, and impaired assets) employed in searching articles. As we focused on the relationship between stranded assets and energy transition, we included "energy transition" or "low-carbon transition" and other terms that represent transition or change, such as "transformation," "phaseout," "exit," "shift," "decommission," "shut down," and "moratoria" in the document search. We also limited the literature by adding seven additional terms ("fossil," "climate," "Paris," "emission," "incumbents," "response," and "option") to ensure our search was not too broad and covered incumbents' perspectives. Finally, we collected articles regarding stranded assets in the energy sector (upstream and downstream).

Furthermore, to obtain the final articles, we conducted several steps, including the following: (i) setting the search to cover the years 1990–2021, (ii) refining the documents based on types of peer-reviewed articles, book chapters, reviews, and books, (iii) limiting the documents to only subject areas of environmental science, energy, social sciences, economics, finance, business, management, and accounting, (iv) excluding documents not written in the English language, (v) manually assessing documents to assemble the relevant results, and (vi) excluding SLR papers, editorial papers, and titles of edited books. From the Scopus and WoS databases, we collected 283 documents. Tables 1 and 2 summarize the literature search results from Scopus and WoS after the refining process.

Data analysis

We employed content and bibliometric methods using VOSviewer, a software developed by the Center for Science and Technology Studies, Leiden University, to support our analysis. We used a LinLog/Modularity method to determine distance-based similarities and create the clusters by focusing on co-occurrence to visualize networks and keywords based on abstract text data. We extended the cluster size to eliminate small and uninteresting clusters to minimize scattered patterns and elicit more detailed relationships among keywords, resulting in three major clusters. This qualitative meta-analysis method provides a concise and comprehensive picture of findings regarding a phenomenon researched in a group of studies (Timulak, 2009, 2014). We synthesize similar studies to unveil the narratives and interconnection of climate change, stranded assets, and energy transition and identify factors influencing the pathways.

Results

Narratives of stranded assets

The emerging narratives can be classified into three clusters, including stranded asset risk in the upstream energy sector (green-colored networks) and downstream energy sector (red-colored networks), and the implications of stranded asset risk on energy transition and options to manage them (blue-colored networks) (Fig. 1). In the first cluster, the upstream sector was highlighted due to its contribution to global carbon emissions. As a result, energy companies and governments

Table 1
Keyword search terms (Scopus)—cutoff date: Dec 31, 2021.

Database	Concept	Keywords	Specific search keywords[a]	Records[b]
Scopus	Stranded assets			235
		stranded assets	("strand*" W/15 "asset*") AND ("energy" OR "low*carbon" W/15 "transition*" OR "transform*" OR "phas*out" OR "exit" OR "shift*" OR "decommission" OR "shut*down" OR "moratori" OR "end*" OR "declin*" OR "reduc*" OR "ban*" OR "displac*") AND ("fossil" OR "climate" OR "Paris" OR "emission*" OR "incumbent*" OR "respon*" OR "option*")	228
		stranded investment	("strand*" W/15 "invest*") AND ("energy" OR "low*carbon" W/15 "transition*" OR "transform*" OR "phas*out" OR "exit" OR "shift*" OR "decommission" OR "shut*down" OR "moratori" OR "end*" OR "declin*" OR "reduc*" OR "ban*" OR "displac*") AND ("fossil" OR "climate" OR "Paris" OR "emission*" OR "incumbent*" OR "respon*" OR "option*")	62
		sunk investment	("sunk*" W/15 "invest*") AND ("energy" OR "low*carbon" W/15 "transition*" OR "transform*" OR "phas*out" OR "exit" OR "shift*" OR "decommission" OR "shut*down" OR "moratori" OR "end*" OR "declin*" OR "reduc*" OR "ban*" OR "displac*") AND ("fossil" OR "climate" OR "Paris" OR "emission*" OR "incumbent*" OR "respon*" OR "option*")	5
	Stranded costs			45
		stranded costs	("strand*" W/15 "costs*") AND ("energy" OR "low*carbon" W/15 "transition*" OR "transform*" OR "phas*out" OR "exit" OR "shift*" OR "decommission" OR "shut*down" OR "moratori" OR "end*" OR "declin*" OR "reduc*" OR "ban*" OR "displac*") AND ("fossil" OR "climate" OR "Paris" OR "emission*" OR "incumbent*" OR "respon*" OR "option*")	32
		sunk cost	("sunk*" W/15 "cost*") AND ("energy" OR "low*carbon" W/15 "transition*" OR "transform*" OR "phas*out" OR "exit" OR "shift*" OR "decommission" OR "shut*down" OR "moratori" OR "end*" OR "declin*" OR "reduc*" OR "ban*" OR "displac*") AND ("fossil" OR "climate" OR "Paris" OR "emission*" OR "incumbent*" OR "respon*" OR "option*")	13
	Impaired assets			10
		asset impairment	("asset*" W/15 "impair*") AND ("energy" OR "low*carbon" W/15 "transition*" OR "transform*" OR "phas*out" OR "exit" OR "shift*" OR "decommission" OR "shut*down" OR "moratori" OR "end*" OR "declin*" OR "reduc*" OR "ban*" OR "displac*") AND ("fossil" OR "climate" OR "Paris" OR "emission*" OR "incumbent*" OR "respon*" OR "option*")	10
Total Scopus				264

[a] The proximity operator "W/15" is used to find various records where the terms joined by the operator are within 15 words of each other. The Boolean operator "AND" finds records containing all terms separated by the operator. The operator "OR" finds records containing any of the terms separated by the operator. The asterisk (*) serves as a wildcard to broaden a search and represent a group of characters, including no character.
[b] Nonitalic numbers are the total number of records excluding duplicates within concepts.

alike in countries with abundant resources benefiting from fossil fuel assets for many years and enjoying significant global political power (Handeland & Langhelle, 2021; Overland et al., 2019) are required to keep their assets in the ground, generating considerable suffering (e.g., currency pressure due to deteriorating trade) (Goldthau et al., 2020), destabilizing their status quo, and threatening economic development (Strambo & González-Espinosa, 2020). In contrast, fossil fuel importing countries will benefit politically and economically from promoting renewable energy at the expense of costly imports (van de Graaf & Bradshaw, 2018); thus, shifting the economic risk of stranded assets to the political risk of stranded geopolitical assets (Overland et al., 2019; Su et al., 2021).

Incumbents in the upstream sector propose a narrative of 'environment vs jobs' as a political action to resist the transition (Goddard & Farrelly, 2018; Pizarro-Irizar et al., 2020; Skoczkowski et al., 2018). Job losses (e.g., coal mining, petroleum refining, and electricity generation from coal and natural gas) will emerge due to the shift away from fossil fuels to renewables and energy efficiency (Montt et al., 2018), which weakens local economies and requires training and education for new jobs (Harper & Snowden, 2017). The impact of stranded assets goes beyond the asset owners, affecting interconnected sectors (Cahen-Fourot et al., 2021; Marsden & Rucinska, 2019) and other forms of assets, mainly in local communities (Harper & Snowden, 2017; Sovacool & Scarpaci, 2016). Early retirement, for instance, not only makes a coal mine a stranded economic asset but also can drain state and local budgets due to compensations and restoration of land and other natural capital assets (water and soil). Thus, stranded costs will be distributed across actors, and the magnitude of loss depends on how significant actors own and rely on the assets for seeking rents.

However, the narrative receives a counterargument that shifting away from fossil fuels promotes job creation opportunities (green jobs). This can be strengthened by engaging with the "just transition" narrative to provide social and economic security for communities (Evans & Phelan, 2016). Since the phaseout triggers incumbents to diversify their businesses, new job opportunities will be created throughout the renewable energy value chain (Semelane et al., 2021). Yet, incumbents need policy support, including subsidies in response to stranded costs, to improve their capacity to offer services and make new investments in the value chain (Semelane et al., 2021).

In response, climate mitigation efforts should be fairly distributed (*climate justice*) to anticipate free-riders (Kartha et al., 2018; Kefford et al., 2018), and attainment of equitable nation-specific emission ceilings designated to all nations is vital to establishing a level playing field (Bos & Gupta, 2016). This issue is related to energy justice (*distributive concept*) to which production cuts should be prioritized in wealthy countries with low dependence on fossil fuel rents over poor countries with a high reliance (*affordability*) or in countries that mismanage their fossil fuel rents considering the resource curse paradigm (*developmental efficiency*) (Le Billon & Kristoffersen, 2020). Hence, climate easement should be given to developing world reserve holders to compensate for stranded resources and maintain the positive impacts of fossil fuels rather than forcing them to explore new areas (e.g., renewables) with high costs and risk, which will adversely affect cash flows (Snyder & Ruyle, 2020). As a result, this can minimize the risks of economic instability and diminish the competitiveness of 'late decarbonizers' due to an 'unjust' transition (Eicke & Goldthau, 2021).

The second cluster demonstrates the downstream energy sector, powered by fossil fuels, as the primary target of decarbonization. In developing and emerging economies (e.g., China, India, Vietnam, Indonesia, and the Philippines), fossil fuel power plants, particularly coal-fired power plants (CFPPs), are relatively newly built in response to growing economies and the need to address energy poverty and security (Chen & Mauzerall, 2021; Manych & Jakob, 2021). However, these CFPPs can be subject to high stranded risk because they are incompatible with the climate target.

Stranding of CFPPs is more urgently required than oil and gas power plants in terms of emissions. However, a problem arises as to whether future energy demand can be met through an increased share of

Table 2
Keyword search terms (WoS)—cutoff date: Dec 31, 2021.

Database	Concept	Keywords	Specific search keywords[a]	Records[b]
WoS	Stranded assets			97
		stranded assets	(“strand*” NEAR “asset*”) AND (“energy” OR “low*carbon” NEAR “transition*” OR “transform*” OR “phas*out” OR “exit” OR “shift*” OR “decommission” OR “shut*down” OR “moratoria” OR “end*” OR “declin*” OR “reduc*” OR “ban*” OR “displac*”) AND (“fossil” OR “climate” OR “Paris” OR “emission*” OR “incumbent*” OR “respon*” OR “option*”)	90
		stranded investment	(“strand*” NEAR “invest*”) AND (“energy” OR “low*carbon” NEAR “transition*” OR “transform*” OR “phas*out” OR “exit” OR “shift*” OR “decommission” OR “shut*down” OR “moratoria” OR “end*” OR “declin*” OR “reduc*” OR “ban*” OR “displac*”) AND (“fossil” OR “climate” OR “Paris” OR “emission*” OR “incumbent*” OR “respon*” OR “option*”)	24
		sunk investment	(“sunk*” NEAR “invest*”) AND (“energy” OR “low*carbon” NEAR “transition*” OR “transform*” OR “phas*out” OR “exit” OR “shift*” OR “decommission” OR “shut*down” OR “moratoria” OR “end*” OR “declin*” OR “reduc*” OR “ban*” OR “displac*”) AND (“fossil” OR “climate” OR “Paris” OR “emission*” OR “incumbent*” OR “respon*” OR “option*”)	4
	Stranded costs			19
		stranded costs	(“strand*” NEAR “cost*”) AND (“energy” OR “low*carbon” NEAR “transition*” OR “transform*” OR “phas*out” OR “exit” OR “shift*” OR “decommission” OR “shut*down” OR “moratoria” OR “end*” OR “declin*” OR “reduc*” OR “ban*” OR “displac*”) AND (“fossil” OR “climate” OR “Paris” OR “emission*” OR “incumbent*” OR “respon*” OR “option*”)	13
		sunk cost	(“sunk*” NEAR “asset*”) AND (“energy” OR “low*carbon” NEAR “transition*” OR “transform*” OR “phas*out” OR “exit” OR “shift*” OR “decommission” OR “shut*down” OR “moratoria” OR “end*” OR “declin*” OR “reduc*” OR “ban*” OR “displac*”) AND (“fossil” OR “climate” OR “Paris” OR “emission*” OR “incumbent*” OR “respon*” OR “option*”)	6
	Impaired assets			1
		asset impairment	(“strand*” NEAR “asset*”) AND (“energy” OR “low*carbon” NEAR “transition*” OR “transform*” OR “phas*out” OR “exit” OR “shift*” OR “decommission” OR “shut*down” OR “moratoria” OR “end*” OR “declin*” OR “reduc*” OR “ban*” OR “displac*”) AND (“fossil” OR “climate” OR “Paris” OR “emission*” OR “incumbent*” OR “respon*” OR “option*”)	1
Total WoS				99

[a] The proximity operator “NEAR” is used to find various records where the terms joined by the operator are within 15 words of each other. The Boolean operator “AND” finds records containing all terms separated by the operator. The operator “OR” finds records containing any of the terms separated by the operator. The asterisk (*) serves as a wildcard to broaden a search and represent a group of characters, including no character.
[b] Nonitalic numbers are the total number of records excluding duplicates within concepts.

renewables and other cleaner technologies (Papadis & Tsatsaronis, 2020; Sovacool & Scarpaci, 2016). In this case, the early retirement policy determines the timeline of CFPPs stranding, although it depends on the government's commitment toward climate goals (Malik et al., 2020). Another problem is investors' perception of the transition. Risk-averse investors in the UK., for example, perceived nuclear power as a bridge to a less carbon-intensive energy mix future as the optimum portfolio (van Zon & Fuss, 2008). This preference hinders the commitment to reduce emissions, indicating weak renewable energy deployment policies (McGlade et al., 2018).

The final cluster reveals the connection between the first and second clusters and their implications. In this cluster, ‘deployment’ is a central issue. Rapid deployment of other cleaner technologies through stringent climate policy is strongly echoed. Technologies sustaining the regime, such as Carbon capture and sequestration (CCS) and Carbon capture, use, and storage (CCUS), have been much discussed as a way to reduce stranded assets and achieve climate targets simultaneously (Pfeiffer et al., 2016, 2018; Wei et al., 2021). Conversely, the availability of low-cost resources and technologies has maintained the share of fossil fuels in global electricity production (Şahin, 2019). Energy security with affordable access (Gupta & Chu, 2018; Sharma et al., 2021) and costs associated with renewable energy deployment possibly hinder a transition away from fossil fuels.

The shift away from fossil fuels also affects the financial market and system. Stranded financial assets due to the expansion of renewables (Ruggiero & Lehkonen, 2017) can increase with sudden changes in market valuation (van der Ploeg & Rezai, 2020). Financial actors undeniably have a crucial influence on the continuation of fossil fuel use (Chen et al., 2020; Jakob et al., 2020; Trencher, Downie, et al., 2020; Trencher, Rinscheid, et al., 2020). In response to renewable energy transitions, they are forced to divest and reprice fossil fuel assets in energy companies. Divestment, however, will be more successful if incumbent governments practically address any shortfalls, usually accomplished via policy measures, beneficial arrangements, and financial support (Curran, 2020).

Energy options in decarbonization: how stranded asset risk affects incumbents' choices

Energy transition pathways are influenced by geopolitical factors; namely, economic conditions, resource endowments, technical capacity, and policy conditions (Charles et al., 2011). Stranded asset risk, wherein incumbents fear financial ruin and increasing transition costs, is linked to such factors. Incumbents have a number of energy options in response to decarbonization; however, they must ensure that the options are affordable, secure, resilient, and dependable.

Fossil fuels: coal

In countries with ample coal resources or dependent on cheap and reliable energy, CFPP is prioritized in the energy mix. Developing and emerging economies, particularly in Asia, are dependent on coal to meet rapidly increasing energy demand. In several developed countries, such as Japan, coal is used to meet energy security to compensate for the disaster of Fukushima's nuclear power generation (Trencher, Downie, et al., 2020). However, countries heavily relying on CFPPs have locked future carbon emissions through existing infrastructure, institutions, and individual behavior (Şahin, 2019), undermining the transition to a clean energy system. Even if coal technologies have developed (e.g., subcritical, supercritical, and ultra-supercritical), they can hinder deep decarbonization. To minimize significant stranded assets in the future, early retirement of CFPP and discontinued newly built infrastructure are critical.

However, phasing out CFPP is complex and challenging. The supportive governments and the domination of energy companies owned by the state and unions or political actors affiliated with the government can delay early retirement, as seen in Poland and Indonesia (Brauers & Oei, 2020; Jakob et al., 2020). Political coalitions, in this case, are a hurdle, mainly in state-dominated energy markets (monopoly) (Kanjilal

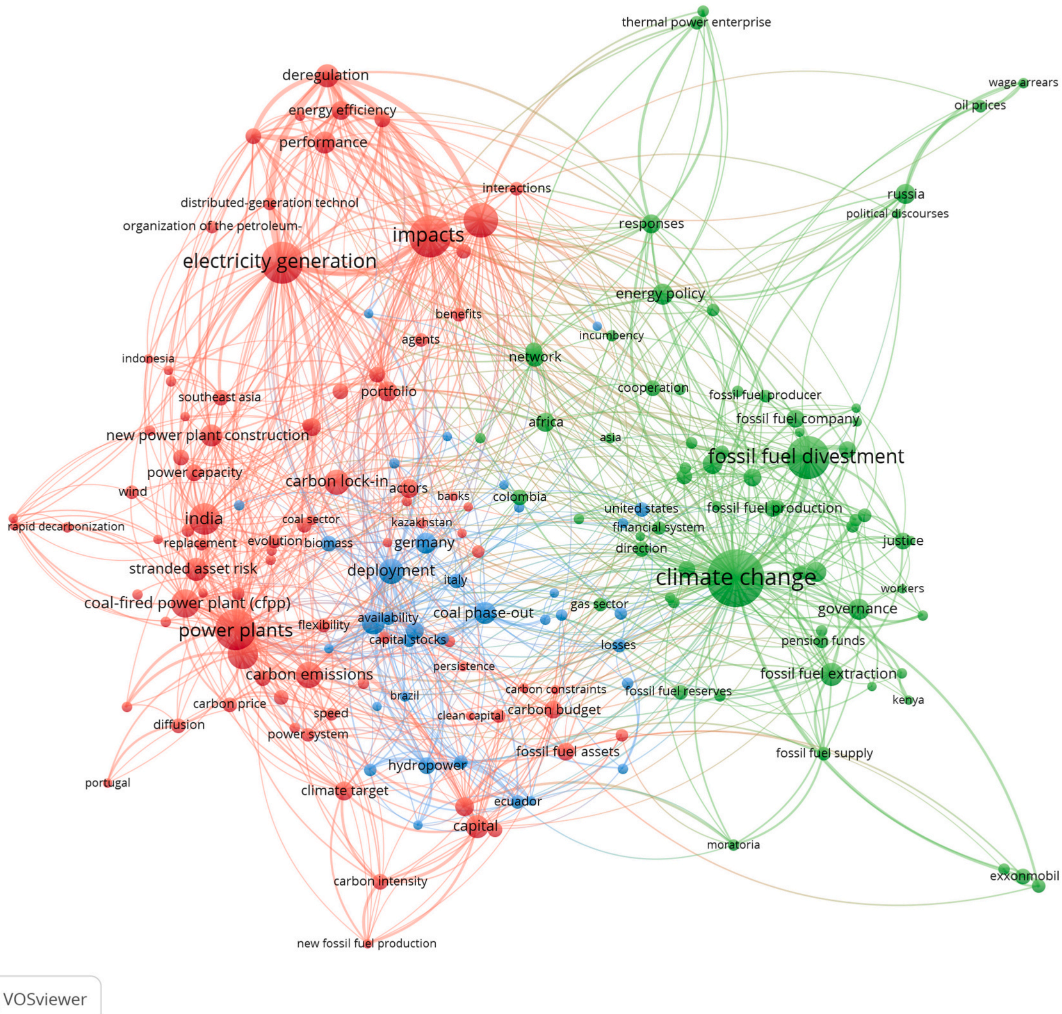

Fig. 1. Co-occurrence of stranded assets and energy transitions.
Source: Authors' elaboration using VOSviewer.

& Ghosh, 2021; Montrone et al., 2021; Nahm & Urpelainen, 2021; Sharma et al., 2021). Policymakers may react to increased renewable energy by formulating new institutional arrangements to protect domestic assets and perpetuate long-term business viability (Trencher, Rinscheid, et al., 2020). This condition particularly applies to countries with abundant coal and strong political-economy tensions between utilities, power producers, and coal suppliers (Jakob et al., 2020; Manych & Jakob, 2021) and implementing long-term power purchase agreements (Trencher, Rinscheid, et al., 2020). Thus, when incumbents receive support from state actors, they tend to align vested interests to benefit from regulation, making the regime resistant to transition (Brauers et al., 2021; Montrone et al., 2021).

Furthermore, perceived high costs, such as the requirement of skilled labor, funding, and economic incentives to build new infrastructure to compensate stranded assets (Rozenberg et al., 2015), prompt incumbents to hinder coal replacement and motivate them to maintain the status quo or lobby the government to recover stranded assets, limiting the expanded use of low-carbon energy technologies. To this, incumbents prevent adverse effects on renewable energy investments unless the government provides compensation (Kefford et al., 2018). Thus, incumbents tend to continue using coal because they are not yet required to bear high stranded assets and transition costs.

Fossil fuels: natural gas

Natural gas is one of the most predominantly used fossil fuels and provides flexibility in many sectors of the economy; primarily in the US, Russia, Europe, and the Middle East (Gielen & Bazilian, 2021). However, as occurred in the EU, gas also faces global market challenges from renewable energy (Marusyk, 2019), although it is promoted as a backup fuel for "renewables" and "reliability of supply" to generate electricity.

The debate regarding natural gas bridging the energy transition process is highly politicized. Natural gas in the EU-Russia energy transition discourse is related to geopolitical issues (Brauers et al., 2021; Marusyk, 2019). While incumbents in the gas industry pursue commercial interests by influencing the shape of energy transitions, various actors benefiting from increased natural gas consumption also prop up pressures (Brauers et al., 2021). In countries where incumbents avoid sunk investments in existing gas infrastructure, they argue technoeconomic for restructuring the system by embracing green gases (e.g., biogas, blue and green hydrogen, and biomethane) (Gielen & Bazilian, 2021). The use of gas to bridge the energy transition proposed in the EU, however, is challenged by the reliance on imported natural gas. The disruption due to deteriorated EU-Russia relations poses a risk to supply security (Szabo, 2022), undermining the role of gas as a bridge to a renewable future. Thus, this questions the reliability of the gas supply to support the energy transition process.

Natural gas cannot be escaped from impairment risks in the future due to lockin and uncertainties related to clean gases in terms of policy, technology, and costs (Brauers et al., 2021; Gielen & Bazilian, 2021; Woollacott, 2020). Supplying natural gas requires investments in reserves, production plants, regasification plants, pipelines, and storage facilities. However, the stranded costs of natural gas assets can be smaller than coal assets because gas plants are less capital-intensive and have shorter lifetimes, so the economic value of gas plants depreciates faster than coal power plants (Binsted et al., 2020).

Fossil fuels with CCS/CCUS

Incumbents, such as energy companies, believe that CCS technology increases the likelihood of reconciling the proliferation of fossil fuel assets with achieving climate targets (Budinis et al., 2018; Pfeiffer et al., 2018) and thus benefits them (Johnsson et al., 2019; Xu & Dai, 2021). In the power sector, the SaskPower's Boundary Dam CCS plant in Canada, for example, successfully passed into the operational phase and cut emissions, although it has not achieved the reduction target (Robertson & Mousavian, 2022). In another energy-use application, the Quest CCS project in Canada for hydrogen production in the refinery experienced declined operating costs of CCS, driven by operational efficiencies (Loria & Bright, 2021). These two examples show the possibility of an alternate technology to the extent of fossil fuel consumption in carbon-constrained scenarios.

Stranded asset risk in fossil fuels becomes lower if CCS/CCUS technology is commercially available. This is because it can add on the existing coal-fired units without significantly adjusting the current system. However, CCS technology can delay decarbonization. Although CCS can reduce direct CO_2 emissions, the power generation efficiency of power plants decreases, posing a substantial barrier to the deployment of CCS (Budinis et al., 2018; Robertson & Mousavian, 2022). Besides, CCS technology will strengthen incumbents' high dependence on fossil fuels, leading to more severe future carbon lockin (Alova, 2020; Karpa & Grginovic, 2021). In addition, it enables incumbents to maintain the regime without disrupting the system and construct a "clean" fossil technology narrative for legitimacy (Trencher et al., 2019; Trencher, Rinscheid, et al., 2020). The government can support this with the same interest in gaining benefits from fossil fuels, leading to regime legitimization (Geels, 2014). Thus, incumbents would prefer fossil fuels while awaiting advances in CCS technology to avoid stranded assets.

Nuclear power

Nuclear can be adopted as an alternative for countries with limited or no fossil fuel resource endowments if reasonably considered and expanded to achieve climate targets (Pizarro-Irizar et al., 2020). It provides energy security and produces fewer emissions than fossil fuels. Stranded asset risk in nuclear power plants is minimal if it is held for future energy mix with the purpose of energy security. Coal power conversion to nuclear (small modular reactors/SMRs) can reduce the costs by re-using or utilizing the existing equipment of coal power plants (retrofit) (Qvist et al., 2021).

However, the coal conversion to nuclear requires significant modifications on the existing steam turbines at coal power plants to fit water-cooled systems at nuclear power plants (Qvist et al., 2021). This leads to additional costs other than initial outlay, maintenance, financing, and decommissioning costs. The costs will decline when modifications are minimal, depending on technology development. Besides, other factors, such as security risks (e.g., proliferation, terrorism), unsolved radioactive waste and limited resource base pressure, as well as the falling costs of low carbon technologies (Child & Breyer, 2016; Farfan & Breyer, 2017b; Helm, 2017), put nuclear power under pressure. In addition, the pathway to nuclear is not in line with the EU energy policy, not to mention eligible for receiving "green" financing schemes (Qvist et al., 2021). Coupled with social pressures regarding the major nuclear accident at Fukushima in Japan, these side effects delay the adoption of nuclear power and even lead to phaseout, as seen in Belgium, Germany, Switzerland, and Scotland (Farfan & Breyer, 2017a; Johnstone et al., 2017).

Renewable energy sources

Incumbents remove fossil fuels from their asset portfolio directly responding to decarbonization, although they have to bear significant stranded assets. These incumbents acknowledge the consequences of climate change in their business, requiring a sound strategy that balances sustainability with profitability (Bach, 2017; Cheon & Urpelainen, 2018). Stringent climate policy, strict enforcement, and social pressures undeniably play a critical role in changing their behaviour, as seen in German electricity giants' responses (Kiyar & Wittneben, 2015).

When the market still adopts the fossil fuel market mechanism, which is not renewable energy-friendly, a low-carbon energy system might hardly be achieved as such conditions undermine market competition and hinder renewable energy development (Guo et al., 2020). The two key features of renewable electricity generating technologies, namely near zero-marginal costs and intermittency, for instance, create fundamentally different cost structures, requiring a different treatment in the current electricity market to stimulate new business models to develop and emerge so it can threaten the vertically integrated incumbent electricity companies (Helm & Hepburn, 2019). Besides, market maturity, including proven regulatory and revenue support frameworks and appropriate infrastructure development policies, is still relevant for accelerating renewable generation deployment, although technologies have advanced (Wright, 2019). These conditions are critical for the market where renewable deployment is at an earlier stage so that barriers to entry for new technologies can be eliminated. However, it should be noted that a competitive market can inevitably lead to stranded costs, mainly from incumbent power market participants (Wright, 2019).

For incumbents, coal is perceived as superior to renewables. This is because renewable-based energy systems are constrained by technoeconomic factors, such as high storage costs and lack of grid stability (Montrone et al., 2021). Besides, the power generated from renewables will be stranded during periods of high generation (oversupply) if not supported by storage availability (Miller & Carriveau, 2019). Solar and wind power, for instance, are from a low base in which only 50 % of total capacity is possible, so a sound combination of dispatchable power, smart demand management, interconnected grids, and storage are needed (Fankhauser & Jotzo, 2018). However, incumbents may invest in renewables to gain the market when renewables arrive at grid parity (Mori, 2021).

Transition pathways toward decarbonization from incumbents' perspectives

The transition can disrupt existing infrastructure and institutions, requiring significant structural adjustment (Fankhauser & Jotzo, 2018). Each energy option has different challenges, mainly related to transition costs, energy security, and sustainability. Incumbents are concerned about transition costs that they have to bear for making new investments in the low-carbon energy system and exiting from the existing energy system. In addition, incumbents with rich natural resource endowments are less likely to turn away from fossil fuels (Ansari & Holz, 2020) as they may avoid being early adopters, considering market and technology risks of new technologies and innovations (Bos & Gupta, 2018; Wright, 2019).

The option of natural gas to achieve a low-carbon energy pathway is close to the old business model, making it a more convenient substitute (Brauers et al., 2021). However, it only offers short-to-medium-term benefits and does not significantly impact emission reduction (Kefford et al., 2018; McGlade et al., 2018; Woollacott, 2020). In addition, additional gas capacities require higher financing costs when taking fossil fuel-related risk into account (Bachner et al., 2019). This pathway is also a relatively weak option, particularly for those relying on imports to meet gas demand. In other words, a disruption in the natural gas supply under strong lock-in will threaten the supply.

The CCS technology can be more competitive if the carbon costs increase (IEA, 2020b). This is because incumbents can sell the captured CO_2 or charge a premium price to consumers to compensate for the high cost of CCS/CCUS projects (Robertson & Mousavian, 2022). However, this option is challenged by several non-technical barriers, such as the costs related to building the location and capacity storage sites, lack of incentives, the absence of CO_2 penalty mechanisms (i.e., a financial penalty for the difference in emission performance between plants with and without CCS), inadequate legal framework to regulate transport and storage, and public awareness and perception, delaying the uptake of CCS technology (Budinis et al., 2018). These barriers make CCS technology relatively more expensive other than capital costs (Budinis et al., 2018; IEA, 2020a).

However, since CCS technology is a fossil fuel-based technology, it can provide energy security (Qvist et al., 2021), meaning that fewer new investments in renewables are required to achieve climate targets while maintaining energy demand. In this case, fossil fuels continue to be used to meet energy demand with a more affordable and reliable supply that renewables cannot replace. Yet, reliance on CCS/CCUS and negative emissions has been criticized because of less concern regarding compliance with the 2 °C target (Strauch et al., 2020), although it can reduce emissions from fossil fuels. Therefore, incumbents are cautious regarding the use of carbon removal technology based on costs and sustainability (Budinis et al., 2018; Fankhauser et al., 2021; Ilinova et al., 2021).

For nuclear power, high costs possibly emerge because of inflexibility, so it is not well-aligned with renewable energy electricity generation (Papadis & Tsatsaronis, 2020). Incumbents, mainly in emerging economies, may not select nuclear power as an option for decarbonization. Moreover, although nuclear power offers energy security and aligns with emission reduction targets, it is unsustainable considering its problem related to long-lived radioactive waste and limited fuel supply (Guttmann, 2018; Harper & Snowden, 2017).

Last, renewable energy might be chosen when incumbents perceive lower costs than conventional fossil fuel power generation. For example, low-carbon power generation technologies may have a high initial capital cost but lower marginal costs (Papadis & Tsatsaronis, 2020; Scholten et al., 2020). Besides, additional costs related to grid integration will become another potential obstacle (Edenhofer et al., 2018). Moreover, from an investors' perspective, negative energy prices due to intermittency affect the return on investments, making investments in renewables riskier and more expensive (Barazza & Strachan, 2020; Scholten et al., 2020). Thus, an extremely derisking renewable may offset high transition costs (Bachner et al., 2019).

However, growing energy demand to support economies requires a reliable energy supply. Since renewable energy system has an intermittent issue if storage technologies with a cost-efficient and environmentally friendly manner are not ready yet (Weber et al., 2016), fossil fuel-based energy systems are dependable in terms of energy security. On the other hand, the pathway to renewable energy system has a technical issue in which the output has a material impact on the running hours of conventional plants; therefore, it requires flexible thermal power plants and seasonal energy storage (Papadis & Tsatsaronis, 2020; Wright, 2019). In other words, renewables will be unable to substitute for many of the services provided by fossil fuels, known as the 'non-substitutability' issue (Albert, 2021).

Furthermore, renewables also have sustainability concerns. For example, the use of biomass for large-scale power plants through coal-to-biomass conversion (re-use of existing infrastructure) requires a sufficient amount of biomass resources (Tzelepi et al., 2020). This may lead to deforestation caused by forest mismanagement (Carvalho et al., 2020) and increased greenhouse gas emissions if the plant is not well designed may hinder the deployment of biomass (Babatunde et al., 2019; Tzelepi et al., 2020). Besides, land competition may occur (Binsted et al., 2020) due to high reliance on biomass feedstock (Qvist et al., 2021). Another example is hydropower, in which physical climate risks may threaten its future use, although it is relatively more dispatchable. However, the pathway to renewables is more sustainable than other pathways as they have the lowest emissions and are compatible with the climate target.

Discussion

Energy options and speed of transitions

Our review reveals that stranded asset risk may discourage incumbents from moving toward a renewable energy-based system. Instead, incumbents will adopt renewables when replacement costs can offset stranded assets. Other factors, such as transition costs, energy security and sustainability concerns, also contribute to incumbents' decisions on a sustainable energy transition. Thus, the closure of the incumbent energy system to reduce emissions and achieve climate goals may lead to several challenges to be considered.

Recent studies mention that it is necessary to rely on a certain energy source to bridge the transition, considering the weaknesses of renewables in providing sufficient electricity supply. Incumbents require clear information about technology development to make decisions regarding energy transitions. As proposed by the literature, using gas as a "backup fuel", for instance, is expected to *bridge the transition* from fossil-based energy to clean and low-carbon energy. However, the bridging phase using gas needs special attention as it leads to conflicting goals in promoting renewables (Bachner et al., 2019). Sokołowski (2018) highlights the energy crisis "electricity vs no electricity" concerning energy security in response to phasing out from the incumbent energy system. This can be amplified if the regulation fails to anticipate the progress of alternative energy development, as seen in European countries, particularly Germany, due to the Russia-Ukraine war. Therefore, it is critical to consider how the energy system evolves, as the speed of change determines whether the transition will occur gradually or rapidly.

Furthermore, the shift away from fossil fuels is still relatively costly in terms of capital and storage technology. Besides, high renewable energy demand in response to the pressure of phasing out fossil fuels, on the other hand, drives increased prices, known as "greenflation", discouraging adoption (Wagner, 2022). In addition, customers may bear a significant cost burden to make the low-carbon energy market sustainable if incumbents pass on the costs due to cost-ineffective generation. This contradicts the "affordable and clean energy" principle in the sustainable energy transition. Achieving energy security with a focus on low-cost energy, unfortunately, perpetuates the fossil fuel regime, so such a target in the transition process should be complemented by a more just and balanced "energy trilemma" to deliver the best outcome for society (Heffron & McCauley, 2017).

Policy implications

The fossil fuel phaseout and the pathway to a sustainable energy system may not come without changes in energy policy. The decision to retire fossil fuel power plants, mainly coal, for instance, depends on the stringency of carbon policies (Sen & von Schickfus, 2020). Sudden policy changes tend to hinder rather than accelerate the energy transition because incumbents cannot anticipate or prepare for the transition. In response, gradual policy change is more likely to generate less disruptive system changes. This is because factors such as sunk costs, uncertainty, investment irreversibility, and market structure influence incumbents' decisions regarding adopting cleaner energy sources.

It is necessary to consider incentives to encourage incumbents to implement green technologies (Abdildin et al., 2021). Policymakers should support phaseout through sound investment and socially protective policies to minimize risk (Auger et al., 2021). The supports include subsidies and infrastructure (e.g., grid) to stimulate a regime to change (Hansen & Pollin, 2020; Healy & Barry, 2017; Semelane et al., 2021). For instance, green credit policies or investment funds can stimulate green innovation and mitigate socioeconomic impacts in carbon-intensive companies (Hu et al., 2021; Semelane et al., 2021).

Besides, policymakers should be responsive to energy technology development. This includes the initiative of a structural transformation of the power market system to accommodate renewables with a supportive energy policy. Thus, the clean and low-carbon energy system can compete with the fossil-fuel-based energy system.

Conclusion

There has been scant attention to the perception of incumbents toward stranded asset risk and its relation to the transition pathways. This study reviews the existing research on stranded asset risk to explore how stranded asset risk influences incumbents' decisions to address sustainability transitions and how energy policy influences decarbonization pathways through their perceived risk. Our findings show that stranded asset risk affects incumbents' decisions to shift away from the fossil fuel energy system to a clean and low-carbon energy system. Other factors, such as transition costs, energy security and sustainability concerns, also contribute to the options for the energy transition pathway. A certain pathway is more likely to be selected by incumbents if it benefits them (e.g., low stranded asset risk and transition costs) but offers a solution to address climate change while maintaining energy security and achieving sustainability. Higher perceived stranded assets will pave the transition toward a renewable energy-based system, but high concerns about transition costs, energy security, and sustainability would retard the transition or direct the system toward different pathways.

However, challenges, such as technology development, including the costs, affect the transition speed. In response, policymakers play a critical role in formulating policy to address such an issue. Besides, policy changes may stimulate incumbents to anticipate or prepare for the transition. The gradual policy change, for instance, is more likely to generate less disruptive system changes, and incumbents would easily accept it. On the other hand, abrupt policy change intensifies regime resistance and energy injustice, but slow change strengthens lock-ins into traditional systems. Thus, stranded assets risk is not a sole consequence of the transition, per se; rather, the structural problem of the existing energy system.

This study may lack articles discussing specific cleaner energy sources or technologies concerning stranded asset risk. This could be related to the coverage of the keywords used in the document search and reliance on only Scopus and WoS databases. For example, articles mentioning renewable energy primarily reference solar and wind, as these energy sources are cleaner than other renewables and widely available.

Nonetheless, the study brings new insights into energy transitions explicitly related to stranded asset risk. As a result, future studies can explore stranded asset risk in a broader context using diverse approaches, and this exploration undoubtedly advances a more comprehensive understanding of existing transition literature and the influence of stranded asset risk.

CRediT authorship contribution statement

Nur Firdaus: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – review & editing, Visualization. **Akihisa Mori:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

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

Acknowledgements

The authors acknowledge funding support from the Japan Society for the Promotion of Science (JSPS) [grant numbers 21H04941]. The authors would also like to appreciate and thank reviewers for their valuable feedback.

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