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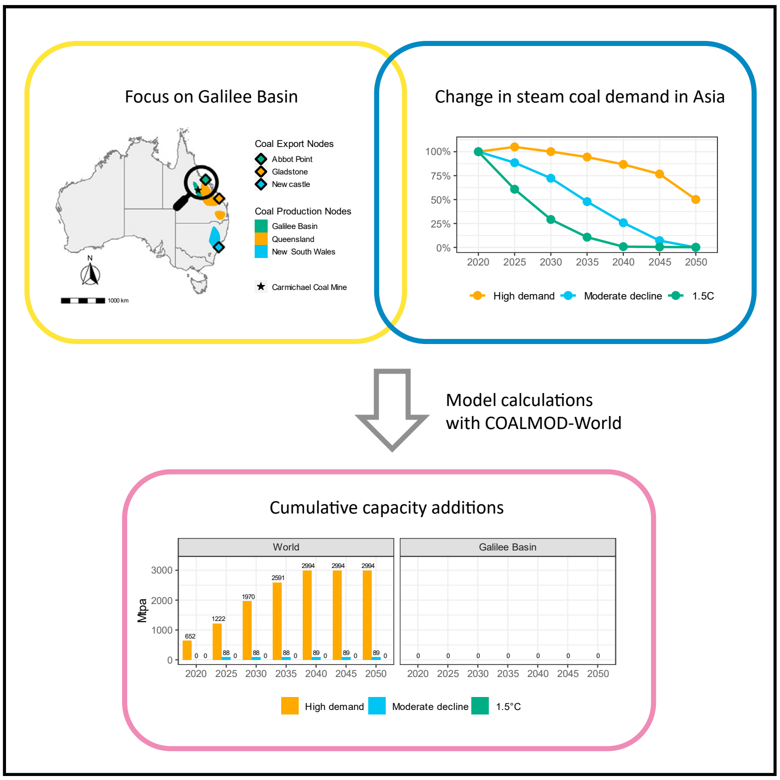
New coal mines in the Australian Galilee Basin are not economically viable and are prone to become stranded assets

Graphical abstract



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In brief

Coal use and trade must decline to limit global warming. The speed of climate-compliant coal phase out and the impact of current developments, such as renewables phase in and aging coal power plant fleets, are uncertain. We show that new coal export projects such as the Carmichael project in the Galilee Basin, Australia, are not economically viable.

Highlights

- Renewables and aging coal power plant fleets lead to decreasing global coal demand
- New coal export projects are still licensed, for example in the Galilee Basin
- Investments in new export projects are not needed in any of our scenarios to 2050
- Galilee Basin coal is not economic due to high costs and shrinking demand in Asia

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New coal mines in the Australian Galilee Basin are not economically viable and are prone to become stranded assets

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SCIENCE FOR SOCIETY Coal is the most carbon-intensive fossil fuel, burning it produces more CO_2 per unit of energy than any other fuel, and thus its continued use as an energy source contributes significantly to climate change. However, despite its negative environmental impacts, governments around the world continue to approve new coal mines, often citing economic benefits. Although the recent European energy crisis did indeed trigger a rise in coal prices, long-term profitability remains highly questionable, particularly in light of global climate policies and rapidly growing renewable energy infrastructure. Using a mathematical model, we assessed the economic viability of Australia's Carmichael project (one of the largest new coal export projects in the world) and show that the project will not break even, even under a high-coal-demand scenario. Our findings demonstrate that short-term economic profitability is not sufficient justification to license future coal projects.

SUMMARY

To limit the effects of climate change, we must significantly curtail the trading and use of coal as an energy source. Although the rise of renewable energy sources has already led to a reduction in the demand for and use of coal, new export-oriented coal mine projects are still being approved, and they often receive strong political support. However, whether these projects are economically viable remains questionable. Here, we leverage one of the largest new coal export projects in the world, the Carmichael project by Adani in the Galilee Basin, Australia, to assess the prospects of investments in coal exports. We use the COALMOD-World model in three scenarios with weak/moderate/strong climate policy ambitions. We find that new coal mines in the Galilee Basin and globally are not economically viable and are prone to become stranded assets due to climate policy and the increasing role of renewables, even in Asia, where the highest coal-demand growth exists. Our findings illustrate the irrational motivations for new coal mines, calling for a cease on coal investments that deliver neither climate nor economic benefits.

INTRODUCTION

Anthropogenic climate change has been recognized as major challenge by the international community. The use of fossil energy resources has contributed a critical share to cumulative human-made greenhouse gas emissions. Coal alone is responsible for about 37% of the global greenhouse gas emissions today.[1] Limiting global warming to 1.5°C of pre-industrial levels requires the rapid decline of coal use over the next decades,[2] leaving no room for new coal mines and the development of the majority of global coal reserves.[3–6] Politically, the climate conference COP26 in Glasgow in November 2021 has heralded the end of coal in the next decades as a global objective. However, national and global climate policies are not aligned with the 1.5°C target so far,[7] and at COP27 in Sharm el-Sheikh in November 2022, the proposal for a global commitment to phase out all fossil fuels was rejected. This ambiguity of global climate policy and the absent end date for a global coal phase out leaves room for different interpretations by coal suppliers and consumers as to the trajectory in the very next years.

Indeed, the world continues to see investments in new coal assets, both for domestic use of coal and for coal exports.[8] If put into operation, proposed new steam coal-mining projects, that is thermal coal excluding lignite, could add some 1,300 million tons per annum (Mtpa) production capacity, an increase in global capacity by up to 20%.[9] However, the economic prospects of new coal assets are highly uncertain. Ratcheting up of climate policies could lead to the stranding of fossil fuel projects.[10–13] Capacity factors of coal-fired power plants have globally decreased over the last decade,[14] as have net additions and plans for new coal plants.[15] Particularly, new export-oriented projects, which account for about one-third to half of all proposed new coal projects,[8] might be affected be declining global demand, as countries with domestic coal production tend to support their domestic supply over imports.[8,16] With coal consumption increasingly concentrated in Asia, coal exporters' prospects highly depend on demand developments in this region.[8,17,18]

The increasing deployment of low-cost renewable energy sources (RESs) and policies tackling coal-related air pollution will contribute to eroding future coal demand.[16,19–21] It remains an open question as to what extent current energy sector developments already pose a stranding risk for new export coal supply assets. Closing this knowledge gap can help to avoid further exacerbating the risk of carbon lock in[22–24] and can help to direct investments into low-carbon energy infrastructure supporting the achievement of climate targets and sustainable development goals (SDGs).[25–27] The same goes for necessary measures to address inevitable structural changes in coal-mining regions.[28,29]

One of the most prominent new export coal projects, and the first mine in the world's largest known, and so far untapped, coal basins, is the Carmichael project by the Indian company Adani in the Galilee Basin in Australia.[30] With its initially proposed annual capacity of up to 60 Mtpa, Carmichael would be one of the largest mines in the world and could cause almost 5 Gt CO_2 emissions over a 60 year lifetime,[31] the equivalent to 1% of the remaining CO_2 budget for limiting global warming to 1.5°C (50% probability).[2] Since its announcement in 2010, the project has received critical attention not only because of its potential climate and environmental impacts but also because of concerns regarding its economic viability.[32–34] In 2022, the first coal was produced from Carmichael. Yet, the question of the project's economic viability remains. Carmichael and other projects in the Galilee Basin might actually risk asset stranding either due to global climate policy or due to current energy sector developments, particularly in Asia. The Galilee Basin's viability in the face of updated demand outlooks is particularly revealing because it gives an indication of the potential profitability of other export projects in the making. Indeed, if the Carmichael project, with its expected economies of scale, is not profitable in reasonable demand outlooks, other, smaller projects are even more unlikely to be viable.

Here, we use the example of the Galilee Basin, which we quantify based on the Carmichael project, to shed light on the prospects of new steam coal export projects using the partial equilibrium model COALMOD-World of the global steam coal market.[3,35] To investigate the uncertainty faced by new export coal projects, we build several detailed, bottom-up coal-demand scenarios, focusing on variation in Asia-Pacific importing countries. Our results show that, even for very low cost assumptions, the Carmichael project is not economically viable. Under none of the assessed plausible scenarios would investments in coal production capacities in the Galilee Basin have been made. Investments in additional coal-mining capacities in other Australian basins are only viable in the highest-demand scenario and only for replacing retired capacities. In the case of a moderately more ambitious climate policy, these replacement investments would also be dispensable. Globally, investments are almost exclusively concentrated on domestic supply capacities, implying a particularly high asset-stranding risk for export-oriented coal supply investments. This is an important message for policymakers to take into account in the licensing of new export projects. They might well be confronted with bankrupt coal companies and local communities suffering from coal-mining dependency within a much shorter time period than expected during a temporary high price period as 2022/2023.

RESULTS AND DISCUSSION

Bottom-up scenarios for future coal demand

Prospects for steam coal supply are strongly linked to developments in the coal power sector, which is responsible for about 75% of the demand.[36] About 80% of this demand originates from the Asia-Pacific region (i.e., Asia and Oceania), and future demand is expected to continue concentrating in this world region.[37] The world's largest steam coal importers are China, India, Japan, South Korea, and Taiwan, together importing some 60% of all internationally traded steam coal.[38] However, strengthened climate targets and increasing shares of renewables might increasingly affect coal demand also in this region.[16,19,20] The amount of new coal power capacities under development has significantly decreased since 2015, and global annual coal power capacity retirements have almost reached parity with capacity additions.[15]

In order to assess prospects of coal export projects in these uncertain market outlooks, we build two coal-demand scenarios based on bottom-up coal sector data and policy information, including data on coal power capacity expansions and retirements from Global Energy Monitor[39] on and information on capacity factor developments (i.e., from Jones, Graham, and Tunbridge[14]). The high demand scenario depicts a continued important role for coal in the current policy environment. The moderate decline scenario represents some more, but limited, climate ambition and an understanding to reduce the role of coal in the long term, in the spirit of the 2021 Glasgow COP26 climate accord. We contrast these two bottom-up scenarios with a 1.5°C scenario based on top-down mitigation pathway

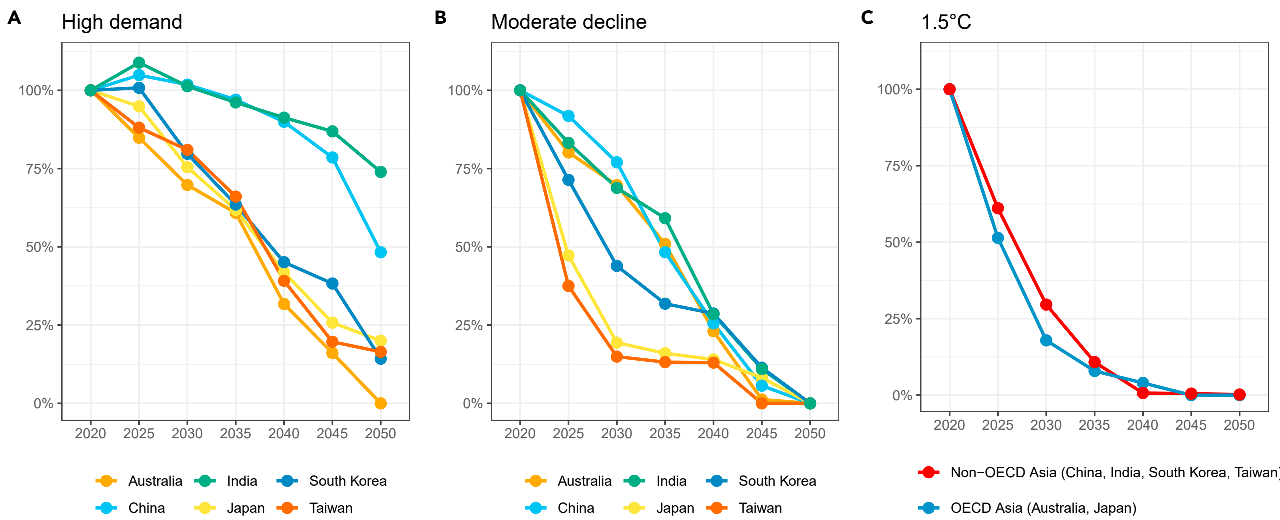

Figure 1. Steam coal-demand scenarios for Asia-Pacific countries
Relative change in steam coal demand until 2050 compared with the year 2020 in Australia, China, India, Japan, South Korea, and Taiwan in the (A) high demand, (B) moderate decline, and (C) 1.5°C scenarios.

analyses from IPCC.[40] Detailed information on scenario building is given in the experimental procedures.

Figure 1 shows the relative changes in steam coal demand until 2050 of five major steam coal importers and Australia in the three scenarios. The decline is delayed in China and India due to coal power capacities under construction coming online in the next years and a younger coal plant fleet. Compared with the high demand scenario, the moderate decline and 1.5°C scenarios show a much faster decline in steam coal demand.

Galilee Basin: Not a profitable venture

We introduce a new node for the Galilee Basin in the COALMOD-World model, which we parameterize based on characteristics of the Carmichael project with the Abbot Point port as the export terminal. Where cost estimates are ambiguous, we use lower-end cost-range values as a starting point for our analysis so as not to artificially disadvantage the project. The initial production capacity as well as the initial transport capacity between mine and port are set to 0 Mtpa in the model. Thus, the decision to build production and transport capacities in the Galilee Basin is endogenous to the model.

We start analyzing the economic viability of the Galilee Basin using the high demand scenario, which is the most favorable scenario for a new project. Yet, no investments into production capacity in the Galilee Basin production node are triggered, despite the low cost assumptions and the scenario with the highest demand in our scenario suite. Considering that each production node in the model represents a profit-maximizing player with perfect foresight over the entire model time horizon, any investment in new production and transport capacities in the Galilee Basin would have a negative net present value.

To test for the sensitivity of the result to future coal-demand assumptions, we also run an even higher demand scenario, based on demand growth rates of the IEA[41] "stated policies scenario" (STEPS) scenario (see Hauenstein[3] for the scenario building). Coal demand remains continuously high in this scenario and approximately represents pre-pandemic industry expectations.[18] Cumulative global coal demand for the time 2020–2050 is 18% higher in this scenario than in our high demand scenario. Yet, also such an exceptionally high demand scenario does not result in the buildup of capacities in the Galilee Basin despite an increase in total Australian production (see Figure S1).

The political economy driving coal export projects

Our quantitative results confirm previous qualitative analyses that found the Carmichael coal mine project to be driven not by economic rationale but rather by political economic objectives, both from actors in Australia as well as in India.[42–44] India has experienced a rapid growth of power demand over the last decades, which has been met mostly by an expansion of coal-fired power generation. However, since the early 2000s, domestic coal production increasingly had fallen behind demand, and Indian steam coal imports have risen.[36] Both state and private actors therefore increasingly looked into securing coal supplies abroad by investing directly into overseas mines and projects, including Adani, which operates several coal plants in India and is well connected to Indian politics.[43]

Similarly, Australian national and state representatives, from all major political parties, welcomed plans for developing additional coal export projects, arguing that they create jobs and economic prosperity.[42,45] The coal sector has developed close ties to all major Australian political parties, which have been sustained by "revolving door" mechanisms for staff between industry, its associations, and the government.[46,47] Stutzer et al.[44] argue that it was also this "enduring symbiosis between the Australian state and the coal industry" that led to the final approval of the Carmichael project in 2019 despite large public opposition to the project. What is more, the national and Queensland governments subsidize the coal sector, including the Carmichael mine, via tax breaks and other subsidies.[47,48]

Table 1. Characteristics of the Carmichael mine and project, including railway transport and exports

Parameter (unit)	Lower bound	Upper bound
Reserves (Mtpa)	2,300	2,300
Energy content (kcal/kg)	4,950	4,950
Initial production capacity (Mtpa)	0	0
Investment cost for new production capacity (million US$/Mtpa)	106	183
Starting value of marginal cost intercept (US$/t)	24	37
Slope of marginal cost curve (US$/$t^2$)	0.15	0.15
Initial rail transport capacity (Mtpa)	0	0
Investment costs for rail transport capacity (million US$/Mtpa)	31.34	40.34
Railway transport costs (US$/t)	7.87	11.36
Initial export capacity (Mtpa)	25	50
Investment costs for additional export capacity (million US$/Mtpa)	8	82
Port fee (US$/t)	4.6	5

Sources and derivation of parameter value ranges provided in Note S2. For all calculations, we use an exchange rate of 1 A$ = 0.7721 US$, which is a representative average exchange rate for the period 2013–2021 (https://www.macrotrends.net/2551/australian-us-dollar-exchange-rate-historical-chart). It excludes the very high exchange rate period around 2010.

Varying the Galilee Basin's investment costs

The result that no investment in the Galilee Basin is profitable in any, not even the highest-demand scenario of our scenario suite, obviously contradicts real-world developments. Adani started producing in and exporting from the Galilee Basin in 2022. Testing the results' sensitivity to our investment cost assumptions, we find that it remains unchanged for a further reduction of unit investment costs by up to 35% in the high demand scenario (see Note S1 for details). In case future demand follows the moderate decline path, a reduction of investment costs between 85% and 90% is required for investments in the Galilee Basin node to become profitable. Thus, almost the entire investment cost, roughly USD_{2015} 1.4 billion in the case of 10 Mtpa production and transportation capacity, would have to be borne by a third party to obtain a positive net present value for the project in a moderate climate policy scenario. However, information on actual investment and production costs of the Carmichael project is scarce, and estimates cover a relatively large range. Costs could be significantly higher than what we take as baseline (compare Table 1), further worsening the economics of the project.

Subsidies as enabler of production in Galilee Basin

In our calculations, we include the known subsidies that were granted to the Carmichael mine (for an estimate, see Buckley[48]) in our investment and production cost estimates, e.g., tax breaks and water rights at reduced costs. However, we cannot rule out that the Carmichael project has benefited from further subsidies or implicit economic guarantees of which we are not aware and that have turned the outlook of the project favorable and, finally, have led to the start of operations in early 2022.

In this spirit, we use the model to investigate whether the Galilee Basin produces and exports coal if investment costs are considered sunk, i.e., if investment costs are not taken into account in the net present value calculations because they do not need to be recovered by the mine's operational profits. Considering investment costs as sunk can be related to subsidization or to a situation where the investor does not see any other, better option than ''writing off'' the past expenditures and going forward. Adani presumably did this in 2018 when downsizing but continuing the project. We conduct additional model runs with an initial production capacity in the Galilee Basin node of 10 or 60 Mtpa included exogenously (i.e., at no cost).

We first assume a ''sunk investment'' of 10 Mtpa production capacity, i.e., 10 Mtpa production capacity is available without investment expenditures in production capacity (see Figure 2 and Note S1). For these model runs, we differentiate between the low and the high production cost estimates (see Table 1). In the high demand scenario, the 10 Mtpa available mining capacity starts to produce at full capacity from the time it becomes available in both cost cases. However, if production costs are high, the available capacity is producing only until 2045 in the high demand scenario and only until 2025 in the moderate decline scenario. It is not used in later years in the moderate decline scenario or in any year in the 1.5°C scenario because global coal demand then is too low. Similarly, sunk investments of 60 Mtpa are used at full capacity in the high demand scenario and in the first years of the moderate decline scenario but not in the 1.5°C scenario (Note S1).

These results show that coal production in the Galilee Basin's Carmichael mine might be profitable for an operator that considers its investment costs as sunk as long as the major coal-consuming countries in the Asia-Pacific region do not reduce their coal use as pledged. If, however, coal consumption in Asia-Pacific goes down in line with the assumptions of our moderate decline scenario (i.e., declining trends of coal plant lifetimes and capacity factors continuing), then long-run profitability of coal production in the Galilee Basin is uncertain, even if ignoring investment costs.

Few brownfield expansions in the rest of Australia

Considering the uncertain outlook for the Carmichael project outlined above, it is more than doubtful that it will serve as stepping stone for the development of more coal-mining projects in the Galilee Basin. However, there is also a large number of proposed new coal mine and expansion projects in the other Australian coal basins in Queensland and New South Wales.[49] These projects differ from the ones in the Galilee Basin because they are in already developed basins and require less investments in transportation infrastructure, etc. Their production also depends largely on export opportunities to the Asian market, where they are in competition with domestic production and other exporters such as Indonesia, Russia, and the USA.

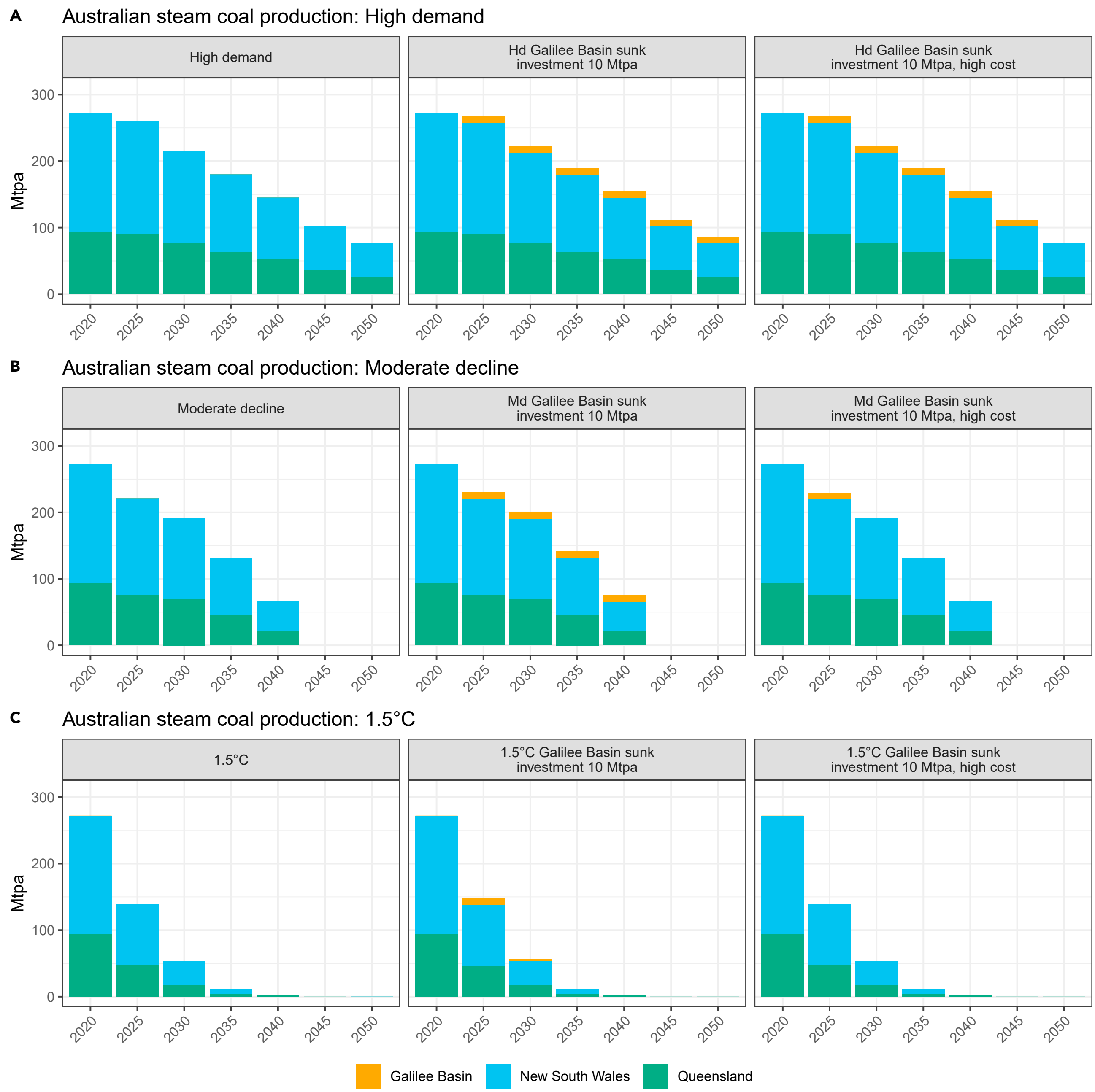

Figure 2. Steam coal production in Australian coal regions
Steam coal production in the Galilee Basin, other Queensland, and New South Wales in the (A) high demand (Hd), (B) moderate decline (Md), and (C) 1.5°C scenarios and for two additional sensitivity runs within each demand scenario (A–C): one considering a sunk investment of 10 Mtpa in the Galilee Basin node (Galilee Basin sunk investment 10 Mtpa), and one considering a sunk investment of 10 Mtpa and high production costs in the Galilee Basin node.

We find that Australian steam coal production has already peaked and falls significantly below the current production level already by 2025 in all three scenarios (Figures 2 and S2). In the moderate decline and 1.5°C scenarios, Australian steam coal production ends within the next two decades, namely by 2045 (moderate decline) or 2040 (1.5°C). In the high demand scenario, Australian production nearly linearly declines from 2020 to about 30% of its 2020 level by 2050.

The trend in Australian production is mirrored by the trend in Australian exports (see Figure S2B), which is due to the coal sector's large export dependency. Currently, 75%–80% of Australian steam coal is exported, of which 90% is shipped to Japan, China, South Korea, and Taiwan.[36] The total export share remains at this high level throughout the entire period in all three scenarios because Australian domestic steam coal demand declines sharply in all three scenarios as well (see Figure S3).

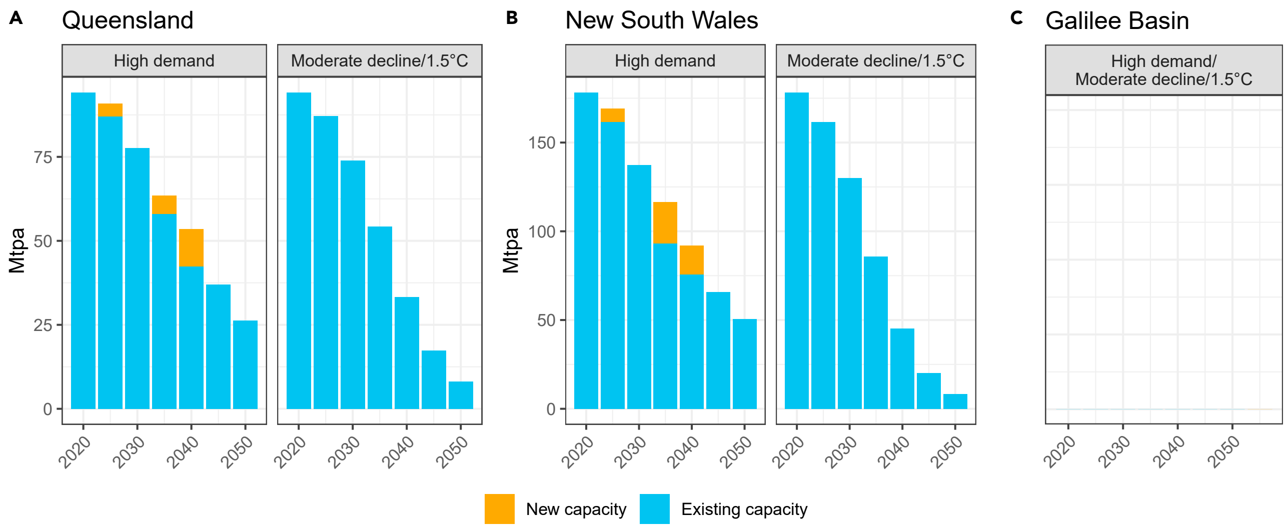

Figure 3. Steam coal production capacity development in Australian coal-mining regions

Available steam coal production capacity in Australian COALMOD-World producer nodes (A) Queensland, (B) New South Wales, and (C) Galilee Basin, in all three scenarios in million tons per year (2020–2050). "New capacity" denotes capacity addition (in year *a*) based on investment in previous model period (year $a-1$). "Existing capacity" denotes remaining capacity from previous model periods.

While investments in new production capacities in the Galilee Basin are not competitive, the model results for the high demand scenario include investments in some 60 Mtpa production capacity between 2020 and 2050 in the other Australian coal basins to replace retiring capacities (see Figure 3). However, both in Queensland and New South Wales, retirement of mines outpaces new investments, and total production capacity declines continuously. In case demand declines faster, such as in the moderate decline scenario, no further investments in capacities in Australia are required or economically viable.

These low replacement investments are in contrast to the large number of proposed production capacity expansions in Australia. As of October 2021, the coal project pipeline in New South Wales and Queensland (excluding the Galilee Basin) contains a total of 16 Mtpa pure steam coal and 22 Mtpa steam and metallurgical brownfield projects, i.e., mine expansions. Additionally a total of 102 Mtpa pure steam coal and 157 Mtpa steam and metallurgical greenfield projects are proposed in Queensland (excluding [excl.] Galilee Basin) and New South Wales.[50] The vast majority of these proposed projects are in an early development stage.[19] These projects would add to what is already a sector with unused capacities. For example, operating mines in New South Wales's largest coal-producing region, the Hunter Valley, are currently operating at less than two-thirds (62%) of their approved capacity,[51] potentially offering some further leeway before making investments into new capacities profitable. What is more, the remaining lifetime of operating coal mines in Australia as reported in Global Energy Monitor[39] likely underestimates their true potential lifetime, as the data are based on the duration of governmental permits for operations and not on available reserves. In turn, required investments could be overestimated for these basins.

Clearly, any investments in new mining capacities further weaken the economic viability of existing operations while being strongly exposed to the risk of asset stranding. This applies to Australia but also to all other world regions. Considering the potential for continued and even additional coal supply from existing Australian mines, investments into new coal-mining projects appear speculative and financially risky. Therefore, in order to avoid an ever-growing share of coal capacities at risk of becoming stranded assets, current Australian expansion plans should be revised.[18] Based on their poor economics, the projects in the Galilee Basin are the most obvious candidates for early scrapping.

Global export coal supply and investment trends

The vast majority of global and Australian steam coal trade is destined for Asia (Figure 4). The global trend toward Asia is amplified in future years due to the stronger energy demand growth in the region compared with other world regions. Australian steam coal exports go almost completely to East Asia, including China, which does not change much over time.

In all scenarios, Australian exports decline substantially below current levels (about 200 Mtpa) in the long run. While in the high demand scenario, exports more than halve until 2050, Australia does not export any steam coal after 2045 and not after 2040 in the moderate decline and 1.5°C scenarios, respectively. In the 1.5°C scenario, global seaborne coal trade decreases fast after 2020, ceasing completely toward 2040. Of the major exporting countries, Colombia and the USA are the first to lose their market shares in the Asian market (already in 2025) due to the high, distance-related supply costs. They are followed by Russia (2030). South Africa continues to cover the remaining Indian import demand, while Indonesia (major share) and Australia (minor share) supply the remaining countries in Asia until 2035.

In the basic setup of our three scenarios, we have not considered a Chinese import ban for Australian coal, expecting that the import ban introduced in 2020 is of temporary nature. In case these restrictions continue, we would expect a continuous rerouting of trade flows within Asia with limited influence on

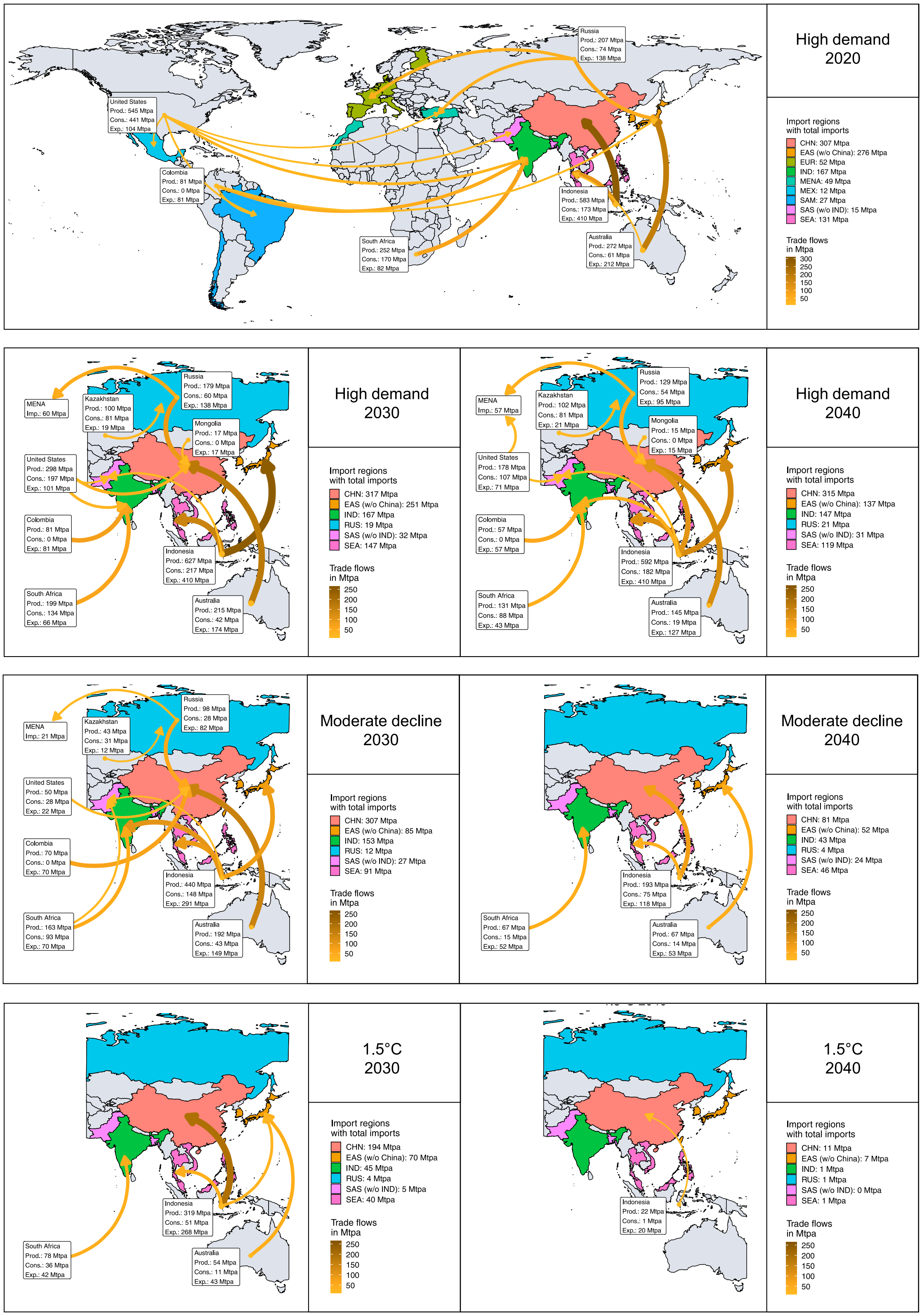

Figure 4. Development of steam coal trade flows in the Asia-Pacific region 2020–2040

Steam coal trade flows in 2030 and 2040 in the three scenarios, high demand, moderate decline, and 1.5°C, compared with trade flows in 2020, as well as regional steam coal production, export, and consumption volumes.

exporters' total production volumes, in particular if high demand in Asia persists. To test for effects of changes in Chinese and Indian import policies, we implemented various sensitivity runs. They show that such import bans would affect Australian exports much more in the moderate decline and the 1.5°C scenarios due to declining imports across the region (see Note S1 and Figure S4).

Global coal production capacities declining

With an increasing share of renewables in the global energy system, global coal demand and production start to decline no later than 2025. In the high demand scenario, this decline is felt differently among the major coal producers. While China, India, and Indonesia continue to produce at an only slightly declining level up to 2040, production in most other major coal-producing and -exporting countries declines by one-third to two-thirds between 2020 and 2040. Yet, these are still high levels compared with the drop in the moderate decline scenario, where global production declines by more than three-fourths between 2020 and 2040, affecting all producers (see Figures S4 and S5 for more details).

This uncertainty of future demand is reflected in the model results for investments in global coal production capacities (Figure 5). In the moderate decline scenario, only some minor investments from 2020 onward (in total, 90 Mtpa) are required in China, while existing production capacities in all other countries are sufficient to cater to the remaining, declining demand. In contrast, in the high demand scenario, investments into new production capacities would be economic in most major producing countries (2020–2050 total of 3,000 Mtpa). However, these are mainly investments in replacements for retired capacities. Capacity expansions would be largely limited to China, India, and Indonesia and to the time until 2025. In other words, large current coal exporters such as Australia, Colombia, Russia, and South Africa face the prospect of stranding their export mine capacities even in high demand scenarios.

In contrast to our model results, there continue to be investment projects in new coal assets, both for domestic use of coal and for coal exports.[8] If built, proposed new steam coal-mining projects could add some 1,300 Mtpa production capacity, an increase in global capacity by up to 20%.[9] Some 380 Mtpa of these planned capacities are expansion projects, but almost 900 Mtpa are in greenfield projects. About two-thirds of the proposed capacities are in Australia, China, and India. Considering the high uncertainty of future coal demand, the risk of asset stranding for new coal mine projects, greenfield and brownfield, is substantial in all countries, not only in Australia and the Galilee Basin. Our findings are in line with other research that points to the increasing risk of stranding for fossil fuel supply assets.[6,10,52,53]

Conclusions

In this article, we assess the economic viability of new coal-mining capacities in the Galilee Basin, particularly of the Carmichael project, and more broadly the prospects of new investments in the export steam coal sector. We find that the Carmichael project is not economically viable. Even if already made investments are considered sunk, profitable long-run operation of the available capacity is uncertain and contingent on continuously high demand in Asia. We show, however, that there is no sustained, long-run demand for additional coal due to decreasing coal-fired power-generation capacities and ever more ambitious climate policies in Australia's traditional export markets—Japan, South Korea, and Taiwan—but also beyond, including in Adani's home market, India. Also, in other Australian coal basins than the Galilee Basin and in other producing countries, there is very limited need for additional investments in coal-mining capacities. While the international community could not agree on a commitment at COP27 in Sharm el-Sheikh in 2022 to raise its ambitions to phase out fossil fuels compared with COP26 in Glasgow in 2021, ratcheting up of climate policies and energy sector regulations in line with the commitments at COP26 would suffice to erase the economic ground for any new coal capacities. With such tight export expansion potentials, any new coal capacities will exacerbate the risk of asset stranding in the sector.

The turmoil on global energy markets, following the Russian attack on Ukraine in February 2022, caused international coal prices to reach unprecedented highs in 2022. Coal producers, and particularly coal exporters, were profiting from significantly increasing profit margins.[54] A continuation of this trend could, thus, also change the economic prospects of new coal projects, such as the Carmichael project. However, in the course of 2022, international coal prices dropped again to levels prior to the Russian attack. We agree with Yanguas-Parra et al.[54] that the time of high coal prices in 2022 will probably remain a short "boom" period for coal producers, which will be followed by a more enduring "bust" period. This will be characterized by lower coal prices, due to overall energy sector developments gradually turning away from coal but also an increasing perception of fossil fuel import dependence as threat to energy security. The latter is also mirrored in the IEA's[55] latest World Energy Outlook in 2022, which emphasizes the need to accelerate the transition away from fossil fuels to improve energy security.

These trends will inevitably lead to a decreasing commitment of financial investors in the fossil resources sector. The fact that Adani had not been able to obtain external funding for the Carmichael project for many years is only the most prominent example of a general industry trend. As of early 2023, Adani shares' values dropped by two-thirds and more after a report raising doubt about the integrity of Adani group's finances and business practices. This might further exacerbate the Carmichael project's uncertain prospects.

The Australian government—just as governments of other coal-exporting countries—has a lesson to learn from the case of the Carmichael project. It shows that coal export projects are far from being a safe bet and come with a high risk of becoming stranded assets, not only due to climate policy but also because of the increasing competitiveness of renewables in the electricity sector. Australia and other coal exporters now have a chance to reduce their fossil resource dependency early enough, while they still have income from this sector to support just transition efforts. A decline in coal production will inevitably be associated with a reduction in jobs in Australian mining regions,[10,56] but the right measures early on can help to smooth the transition for affected workers and communities.[28,29] Richter, Mendelevitch, and Jotzo[57] discussed that an export tax or a production tax in Australia and elsewhere could provide tax revenue while having some attenuating effect on global coal supply and, hence, greenhouse gas emissions.

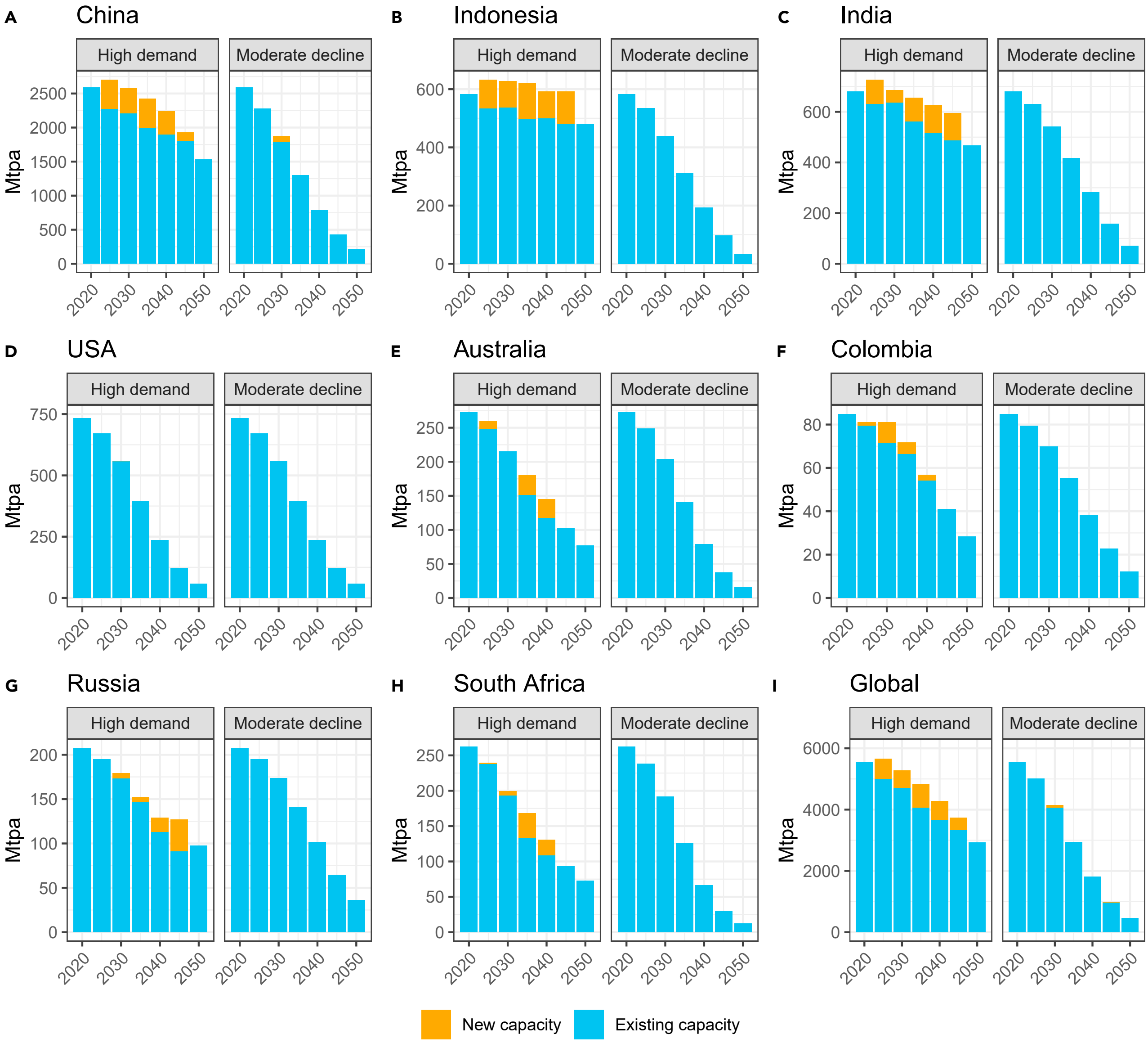

Figure 5. Steam coal production capacity development in major coal-producing countries

Available steam coal production capacity in (A) China, (B) Indonesia, (C) India, (D) USA, (E) Australia, (F) Colombia, (G) Russia, (H) South Africa, and (I) globally in the high demand and moderate decline scenarios in million tons per year (2020–2050). "New capacity" denotes capacity addition (in year *a*) based on investment in previous model period (year $a - 1$). "Existing capacity" denotes remaining capacity from previous model periods. The 1.5°C scenario is not shown because no new capacity was added. Retirement of existing capacity follows the same retirement curve as in moderate decline scenario.

There are some limitations to observe with respect to our analysis. First, we focus on the physical assets in the coal sector, and we use an equilibrium model setup to assess the risk of asset stranding. However, coal supply assets can also be at risk of financial stranding due to the coal market's price volatility, as observed repeatedly in the past, for example in 2021 in Australia and during the 2010s in the USA.[21] Second, a major caveat of model-based analyses is the limited quality of available data. With the publication of the "Global Coal Mine Tracker,"[39] openly accessible data on coal mines have been greatly advanced. However, data on the technical lifetime of existing mines is still scarce, so our results for required coal mine replacement investments have to be considered with some care (also, compare Hauenstein[3]). Lastly, while our model results suggest that there is no economic case for the Carmichael project, the first coal from the project has been produced. As our analysis shows, an explanation could be that early project investments are considered sunk, leaving them out of further profitability calculations. Another factor could be that coal investors still seem to take their investment decisions based on high demand forecasts, and the volatile commitment to climate policy in several Asian countries has repeatedly provided them reasons to do so. And, last but not least, interlinkage between the coal sector and the political decision-makers might have provided further reasons for the project to move ahead, but there is still a need for more research on this. Transparency on costs, stakeholders, and expected externalities is what can help the public to understand the interests and stakes in such a project.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

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Materials availability

This study did not generate new unique materials.

Data and code availability

The model code used in this analysis is openly available in Hauenstein.[58] All data and figure code are provided in Hauenstein et al.[59]

The Carmichael mine in the Galilee Basin in Australia

The Galilee Basin is a steam coal basin in central Queensland in Northeastern Australia whose coal deposits were first discovered in the 1970s. The basin is relatively remote and lacked infrastructure required for mining. To open up the Galilee Basin for coal production, long rail lines across floodplains and farmland had to be built, resulting in comparatively high investment and transportation costs. Additionally, the low availability of water as well as the lack of air and road transportation and power and mining infrastructure required large upfront investments.

In 2010, Adani's application process for the Carmichael mine began, and since then, the project has gone through numerous reviews and project changes. This makes it challenging to define the costs and capacity numbers. The Carmichael project includes up to six open-cut coal pits, five underground mines, coal-processing facilities, and a railway line from the mine to the Abbot Point coal export terminal.[60]

The Carmichael project was downsized several times and most drastically in 2018 after the company failed to attract external funding. The project's investment volume then was reduced from A$16.5 to A$2 billion by reducing the mine's initial production capacity from 60 to 10 Mtpa with plans to ramp up production capacity to 27.5 Mtpa later. In addition to the A$2 billion invested by Adani, the Carmichael mine benefits from subsidies from the Australian and Queensland governments. For a project size of 27 Mtpa, the subsidies were estimated to amount to approximately A$4.4 billion over a 30 year project lifetime.[48] Most subsidies are tax breaks and reduced fees for public services, for example for water rights. In June 2019, the Carmichael project was granted its final environmental approval. After the announced beginning of the mine's operation had been postponed several times, Adani commenced the construction of the mine in 2019 and produced its first coal in early 2022.

Given the possible role model function of the Carmichael mine for other Galilee Basin projects, we base our subsequent analysis on cost estimates and other data for the Carmichael project. Also, we use the characteristics of the Abbot Point terminal for coal export port data of the Galilee Basin. Table 1 provides an overview of the main parameters for the Carmichael project. We include lower-bound and upper-bound estimates where there is uncertainty on the parameter values. Details on parameter value derivation and on value ranges, as well as more background information on the Galilee Basin including Carmichael and other coal mine projects, can be found in the supplemental information (Note S2).

Let us highlight a few data points from Table 1. First, Carmichael coal has a relatively low average energy content of 4,950 kcal/kg (net as received [NAR]).[61] This is 17.5% lower than the standard Australian benchmark coal (exports via the Newcastle port) with an average energy content of 6,000 kcal/kg.[62]

Second, there is a considerable spread between the lower-bound and the upper-bound estimates of investment costs in production capacity (mine) and export capacity (Abbot Point port) and, to a lesser extent, also in railway transportation capacity. However, these spreads are not due to the potentially diverging nature of the data sources. Rather, these data were taken from different stages of the project planning. Generally, the downsizing of the Carmichael project over time—only developing more easily accessible parts of the mine and the shorter railway line, the expansion of only the existing export terminal—has led to lower investment costs by Mtpa annual capacity (which, however, would question the scalability of the mine to 60 Mtpa capacity at these low unit investment costs).

Third, there is also much uncertainty on the operational costs, with upper bounds of production (mining) and railway transport costs about 50% higher than the lower-bound estimates. The lower-bound estimates for combined Galilee Basin operational supply costs (free on board (FOB): production + railway transport + export port fee) are in the same range as the FOB costs of the other Australian suppliers from New South Wales and Queensland but are slightly higher than other suppliers to the Asian market. The upper-bound estimates, however, are more expensive than all other major suppliers to the Asian market.

The COALMOD-World model

COALMOD-World (CMW) is a partial equilibrium model of the world steam coal market (see Hauenstein[3] for a detailed description of the model version used here and Holz et al.[35] for further model background information). The model includes all major steam coal producers, trade routes, and consumers. Producers and exporters are represented as profit-maximizing players with perfect foresight under specific operational and technical constraints. Consumption nodes are represented via inverse demand functions, based on exogenously derived (scenario-specific) coal-demand levels. Market-clearing conditions endogenously determine regional coal prices. Production and trade volumes, as well as investments in production and transport infrastructure, are endogenous model decisions. Investments in additional capacities are made if profitable over the model horizon (net present value optimization). The added capacity becomes available in the subsequent period after the investment decision is made. Production capacities are retired once they reach the end of their technical lifetime, as introduced in Hauenstein.[3] Producers face specific extraction costs, age structures of their existing mine capacities, remaining coal reserves, coal qualities, and expansion potential per period. In accordance with findings of previous studies,[63,64] the steam coal market is modeled as perfectly competitive. The model is calibrated for its starting year 2015.

While the model formulation generally focuses on operational and technical constraints, we include one politically defined constraint on the total amount of Chinese coal imports (for details, see Hauenstein[3]). Although not officially announced, China *de facto* restricts the amount of coal imported.[19,65] We include an import quota that restricts all international seaborne imports into China to 300 Mt per year. This value is derived from import volumes in recent years and is a rather conservative, large quota. Results of Gosens, Turnbull, and Jotzo[65] and recent media announcements suggest even lower quotas in future years (compare Note S1).

The Galilee Basin is introduced as one additional producer node. It is the third producer node in Australia, in addition to New South Wales and (the rest of) Queensland (Figure 6). The dedicated export terminal of the Galilee Basin node is Abbot Point. The Galilee Basin producer node is parameterized based on Adani's Carmichael project. In order to analyze the economic viability of the construction and operation of the Galilee Basin, the initial production capacity (in 2015 and 2020) as well as the initial transport capacity are set to 0 Mtpa. This means that investments are required before starting any mining operations. Moreover, where ranges of data values were assessed, we use lower-end cost estimates and higher-end available capacity estimates in order to not underestimate the investment potential in the Galilee Basin.

Coal demand and scenarios with a focus on Asia

As the world's second largest steam coal exporter, Australia plays a major role for the coal supply in Asia. Japan, China, South Korea, Taiwan, and India (in descending order) are the main destinations of Australian coal.[67] In 2019, almost 90% of Australia's steam coal exports were shipped to these countries.[68,69]

Table 2 gives an overview of steam coal consumption, production, and imports from Australia in 2019, as well as of coal and climate policies and targets of main consumers of Australian steam coal. China and India alone account for two-thirds of global steam coal consumption, but they can supply most of the coal they need through domestic production. Japan, South Korea, and Taiwan, in contrast, have no domestic coal reserves and are heavily dependent on imports.[69] Large parts of their coal imports have traditionally come from Australia.

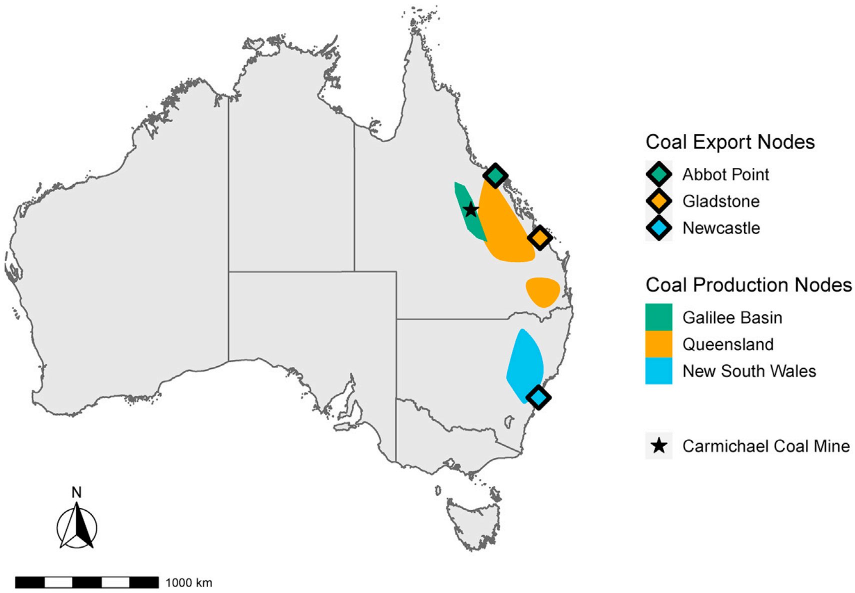

Figure 6. COALMOD-World coal production and export nodes in Australia

Map shows location of Australian coal production regions and export harbors as depicted in COALMOD-World. Source: our own illustration. Geographical data from Australian Bureau of Statistics.[66]

While coal continues to be a major energy source in many Asian countries, the coal sector has come under increased pressure due to cheaper alternative power sources, as well as strengthened environmental and climate targets.[16,19,20] Globally, coal plant utilization (capacity factor) has declined between 2010 and 2019 from 60% to 51%. In China, the average capacity factor of coal plants has even fallen below 50% since 2015. In India, it is still higher but has dropped from 76% in 2010 to 57% in 2019.[14]

Ever since a record high number in 2015, commissioning of new coal capacity has dropped to a low level not seen since 2005.[81] Global coal power capacity under development has declined by about 1,000 gigawatt (GW), or 66%, between 2015 and 2020, while in the same time, around 1,000 GW planned coal capacity additions were canceled,[81] and this trend has continued dynamically since 2020. Around COP26 in late 2021, China, that is the last major provider of public finance for overseas coal projects, announced an end to this funding, following earlier commitments of Japan and South Korea. This would leave only 22 GW planned new coal capacities in Asia outside of China and India by the end of 2021 (not considering projects already under construction) if all formerly Chinese-finance-backed plans are canceled, and of these remaining planned 22 GW, only a minority of them have secured financing.[82]

With a slowdown of capacity additions, the coal plant fleet is aging in most countries. While in China and most South and South-East Asian countries, excluding India, the average age of operating coal units is only around 10 to 12 years (as of January 2021), it is 16 years in India and South Korea and 21–23 years in Japan and Taiwan. Thus, more and more units reach the average retirement age, which is now as low as 22 years in China but 35 years in other East Asian countries and 43 years in India.[39]

Furthermore, Australia, Japan, South Korea and Taiwan have announced plans to achieve greenhouse gas neutrality by 2050, while China aims for 2060 and India for 2070. However, only South Korea has announced an explicit coal phase-out target (by 2050), while some of the other countries have set intermediate energy sector targets. Australia and India have not announced any concrete plans to phase out coal power. Similarly, despite the high gains in public health, water consumption, and other indicators that China could expect from a rapid coal phase out,[83] the largest coal-consuming (and -producing) country so far has only seen vague announcements of peaking coal use and emissions before 2030. A more detailed description of the steam coal demand and the climate policies in each of the major coal countries in the Asia-Pacific is provided in Note S3.

Scenario design

Based on the above outlined developments, we design three plausible but diverging global coal-demand scenarios, which are the aggregate of national and regional trends (Table 3). The high demand scenario, with a continued important role for coal in a current policy environment, is contrasted with a 1.5°C scenario, where coal phase out is the result of ambitious emission reduction targets. Furthermore, we define the moderate decline scenario as an intermediate coal-demand scenario, which is based on limited climate ambitions and an understanding to reduce the role of coal in the long term, in the spirit of the 2021 Glasgow COP26 climate accord. All scenario input data files are available in Hauenstein et al.[59]

We design coal-demand pathways for each Asian market as part of the global coal-demand scenarios (high demand and moderate decline) based on their national coal and energy sector specifics, as well as their energy and climate policies. Such bottom-up scenarios provide more plausible ranges of future coal demand by considering physical infrastructure constraints and regional, sector-specific developments than do aggregated energy system and general equilibrium models.[88] As the 1.5°C mitigation scenario requires unprecedented changes of the energy sector in many Asian countries,[89] we therefore rely on IPCC[40] data for our 1.5°C scenario. In all scenarios, consumption levels for the year 2020 are based on extrapolated 2015–2019 regional coal-demand trends.[90] We, thereby, intend to smooth the short-term COVID-19 effect on coal markets in 2020.[91,92]

Table 2. Overview of main Australian coal-importing countries and Australia

Indicator	AUS	CHN	IND	JPN	KOR	TWN
Steam coal consumption in 2019 (Mtpa)[69]	55	3,315	866	141	102	59
Steam coal production in 2019 (Mtpa)[69]	271	2,970	678	1	1	0
Steam coal imports in 2019 (Mtpa)[69]	0	232	183	140	102	60
Imports from Australia in 2019 (%)[a]	–	38	2	57	31	40
Coal phase-out or -down schedule	–	peak in 2025[70]	–	−46% (2019–2030)[b]	phase out by 2050[71]	−33% (2019–2025)[c]
Carbon-neutrality target date	2050[72]	2060[73]	2070[74]	2050[75]	2050[76]	2050[77]

AUS, Australia; CHN, China; IND, India; JPN, Japan; KOR, South Korea; TWN, Taiwan.
[a]Share of Australian coal in total imports of the respective country. Our own calculations with data from IEA.[68,69]
[b]Our own calculations with data from METI[78] and Argus Media.[79]
[c]Our own calculations with data from the MOEA Bureau of Energy.[80]

Table 3. Overview of coal-demand scenarios and their coal power plant assumptions

	High demand	Moderate decline	1.5°C
Asian countries[a]	assumed lifetime: 40 years (South Korea: 30 years)[b]; capacity factors: linear reduction to 50% by 2050 (China: 40%), thereafter constant	assumed lifetime: 25 years; capacity factors: linear reduction to 40% by 2030, thereafter constant	based on IPCC[40] 1.5°C mitigation scenarios analyzed by Parra et al.[84]
Australia	based on the central scenario in the AEMO 2020 Integrated System Plan[85]	based on the fast change scenario in the AEMO 2020 Integrated System Plan[85]	based on IPCC[40] 1.5°C mitigation scenarios analyzed by Parra et al.[84]
Rest of the world	based on the stated policies scenario in the IEA World Energy Outlook 2020[86]	based on the sustainable development scenario in the IEA World Energy Outlook 2020[86]	based on IPCC[40] 1.5°C mitigation scenarios analyzed by Parra et al.,[84] i.e., median unabated coal consumption of 1.5°C scenarios fulfill additional sustainability criteria (no or limited temperature overshoot; limited BECCS and carbon uptake from AFOLU)

[a]Asian countries represented in the COALMOD-World model are Bangladesh, China, Indonesia, India, Japan, Malaysia, Pakistan, Philippines, South Korea, Taiwan, Thailand, and Vietnam.
[b]South Korean "Basic Plan for Long-term Electricity Supply and Demand."[87]

For the high demand and moderate decline scenarios, we calculate future steam coal generation capacity in Asian countries based on unit-level coal-fired power plant data from the Global Coal Plant Tracker provided by Global Energy Monitor.[39] We assume that coal-fired generation units will retire in the announced year, if a shutdown date is available in the data. For all other units that are operating or are under construction, we assume the retirement after 40 years of operation in the high demand scenario, the conservative benchmark used also by Clark, Zucker, and Urpelainen[93] and Global Energy Monitor et al.[81] An exception is South Korea, where we assume an average retirement age of 30 years, which corresponds to the planned operational lifetime in the government's "Basic Plan for Long-term Electricity Supply and Demand." In the moderate decline scenario, we assume the retirement after 25 years of operation for units without announced retirement dates, based on the low average retirement age of coal plants observed in recent years, in particular in China.

We exclude planned power plants that are not yet under construction, assuming that the large majority of these projects will be scrapped before starting production. This assumption differs apparently from the IEA assumption and leads to lower 2050 coal demand in Asia in our high demand scenario than in the IEA WEO STEPS scenario.

For capacity factors of coal power generation, we assume a further reduction based on the falling trend of the last years and depending on climate policy ambitions. In the high demand scenario, we use a linear reduction of the current capacity factors to 50% by 2050 (except for China), remaining constant thereafter. For China, where the capacity factor is already below 50% today, we assume a linear reduction to 40% in 2050. For those countries where no current capacity factor is available, we assume a current capacity factor of 55% based on the "rest of the world" factor from Jones, Graham, and Tunbridge.[14] For the moderate decline scenario, we assume a significantly faster decline of the capacity factory, which is linearly reduced to 40% in 2030 and then remains at this level until 2050.

For Australian domestic coal demand, we use scenario data of the 2020 Integrated System Plan (ISP) by AEMO.[85] For our high demand scenario, we use their "central scenario," which predicts a coal-demand decrease determined by current policies. As the data in this scenario only go to 2042, we continue the trend linearly to 2050 when Australian coal demand falls to zero. For the moderate decline scenario, we use their "fast change scenario," which assumes a fast energy transition and both national and international strategies to reduce future CO_2 emissions.[85] It predicts an almost linear decline of Australian steam coal demand beginning in 2020 and reaching zero by 2045. One can reasonably expect even an accelerated decline in Australian coal demand since the government announced in the fall of 2021 to close some 5 GW coal-fired power capacity even before their original shutdown date.[94] The draft of the latest 2022 AEMO ISP also assumes a much faster decline in Australian coal demand than was estimated in the previous report, which informed our scenarios. The path considered "most likely" by stakeholders in the new draft expects a rather fast transition from fossil fuels to renewable energies, which leads to an almost complete end of steam coal-fired power generation by 2040.[95]

For all other countries, we use steam coal-demand trend data of the IEA[86] STEPS for our high demand scenario and of the "sustainable development scenario" (SDS) for our moderate decline scenario. STEPS is based on current and stated policies and does not aim at meeting climate targets. It anticipates a rapid recovery from the COVID-19 pandemic and expects gross domestic product (GDP) after 2021 to be as high as before the pandemic. The share of renewable energies is assumed to grow, but coal will still account for about 30% of global power supply in 2040.[86] The SDS, in contrast, foresees a more sustainable recovery from the pandemic. It projects a significant increase in renewable energy investment over the next decade, with coal accounting for about 8% of global power supply in 2040.[86]

We also design a climate policy scenario with an effective coal exit, the 1.5°C scenario. It is based on the IPCC[40] special report on 1.5°C scenarios. Yanguas Parra et al.[84] selected those 1.5°C scenarios that also fulfill other sustainability criteria such as reasonably limited use of biomass with carbon capture and storage (BECCS) and limited carbon uptake from afforestation or land use. For each model year (i.e., 2025, 2030, 2035, and so on), we take the regional growth rates of the median global coal consumption of these selected scenarios.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.07.005.

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AUTHOR CONTRIBUTIONS

Conceptualization, C.H. and F.H.; methodology, C.H. and F.H.; formal analysis, C.H., L.R., and T.M.; data curation, C.H., L.R., and T.M.; writing – original draft, C.H., F.H., L.R., and T.M.; writing – review & editing, C.H. and F.H.; visualization, C.H. and T.M.; funding acquisition, C.H. and F.H.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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REFERENCES

1. Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I.T., Olsen, A., Peters, G.P., et al. (2022). Global Carbon Budget 2022. Earth Syst. Sci. Data *14*, 4811–4900. https://doi.org/10.5194/essd-14-4811-2022.
2. IPCC (2022). In Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. Mc- Collum, M. Pathak, S. Some, P. Vyas, and R. Fradera, et al., eds. (Cambridge University Press). https://doi.org/10.1017/9781009157926.
3. Hauenstein, C. (2023). Stranded assets and early closures in global coal mining under 1.5°C. Environ. Res. Lett. *18*, 024021. https://doi.org/10.1088/1748-9326/acb0e5.
4. IEA (2021). Net Zero by 2050: A Roadmap for the Global Energy Sector (International Energy Agency). https://www.iea.org/reports/net-zero-by-2050.
5. Trout, K., Muttitt, G., Lafleur, D., Van de Graaf, T., Mendelevitch, R., Mei, L., and Meinshausen, M. (2022). Existing fossil fuel extraction would warm the world beyond 1.5 °C. Environ. Res. Lett. *17*, 064010. https://doi.org/10.1088/1748-9326/ac6228.
6. Welsby, D., Price, J., Pye, S., and Ekins, P. (2021). Unextractable fossil fuels in a 1.5 °C world. Nature *597*, 230–234. https://doi.org/10.1038/s41586-021-03821-8.
7. UNEP (2022). Emissions Gap Report 2022: The Closing Window — Climate Crisis Calls for Rapid Transformation of Societies (United Nations Environment Programme). https://www.unep.org/emissions-gap-report-2022.
8. International Energy Agency (2022). Coal 2022 - Analysis and Forcast to 2025 (OECD). https://www.iea.org/reports/coal-2022.
9. Global Energy Monitor (2022). Global Coal Mine Tracker. https://globalenergymonitor.org/projects/global-coal-mine-tracker/.
10. Auger, T., Trüby, J., Balcombe, P., and Staffell, I. (2021). The future of coal investment, trade, and stranded assets. Joule *5*, 1462–1484. https://doi.org/10.1016/j.joule.2021.05.008.
11. Bretschger, L., and Soretz, S. (2022). Stranded Assets: How Policy Uncertainty affects Capital, Growth, and the Environment. Environ. Resour. Econ. *83*, 261–288. https://doi.org/10.1007/s10640-021-00632-3.
12. Edwards, M.R., Cui, R., Bindl, M., Hultman, N., Mathur, K., McJeon, H., Iyer, G., Song, J., and Zhao, A. (2022). Quantifying the regional stranded asset risks from new coal plants under 1.5 °C. Environ. Res. Lett. *17*, 024029. https://doi.org/10.1088/1748-9326/ac4ec2.
13. van der Ploeg, F., Rezai, A., and Rezai, A. (2020). The risk of policy tipping and stranded carbon assets. J. Environ. Econ. Manag. *100*, 102258. https://doi.org/10.1016/j.jeem.2019.102258.
14. Jones, D., Graham, E., and Tunbridge, P. (2020). Global Electricity Analysis H1- 2020 (EMBER). https://ember-climate.org/wp-content/uploads/2020/08/Report-Ember-Global-Electricity-Review-H1-2020.pdf.
15. Global Energy Monitor; CREA; E3G; Sierra Club; SFOC; Kiko Network; CAN Europe; LIFE; Bangladesh Groups (2022). Boom and Bust 2022: Tracking the global coal plant pipeline. https://globalenergymonitor.org/wp-content/uploads/2022/04/BoomAndBustCoalPlants_2022_English.pdf.
16. Yanguas Parra, P., Hauenstein, C., and Oei, P.-Y. (2021). The death valley of coal – Modelling COVID-19 recovery scenarios for steam coal markets. Appl. Energy *288*, 116564. https://doi.org/10.1016/j.apenergy.2021.116564.
17. Chen, X., and Mauzerall, D.L. (2021). The Expanding Coal Power Fleet in Southeast Asia: Implications for Future CO_2 Emissions and Electricity Generation. Earth's Future *9*, 12. https://doi.org/10.1029/2021EF002257.
18. SEI; IISD; ODI; E3G; UNEP (2021). The Production Gap Report 2021. http://productiongap.org/2021report.
19. International Energy Agency (2021). Coal 2021 - Analysis and Forcast to 2024 (OECD). https://www.iea.org/reports/coal-2021.
20. Littlecott, C., Roberts, L., Şenlen, Ö., Burton, J., Joshi, M., Shearer, C., and Matt, E. (2021). No New Coal by 2021: The Collapse of the Global Coal Pipeline (E3G). https://www.e3g.org/publications/no-new-coal/.
21. Mendelevitch, R., Hauenstein, C., and Holz, F. (2019). The Death Spiral of Coal in the U.S. Will Changes in U.S. Policy Turn the Tide? Clim. Pol. *19*, 1310–1324.
22. Erickson, P., Kartha, S., Lazarus, M., and Tempest, K. (2015). Assessing carbon lock-in. Environ. Res. Lett. *10*, 084023. https://doi.org/10.1088/1748-9326/10/8/084023.
23. Fisch-Romito, V., Guivarch, C., Creutzig, F., Minx, J.C., and Callaghan, M.W. (2021). Systematic map of the literature on carbon lock-in induced by long-lived capital. Environ. Res. Lett. *16*, 053004. https://doi.org/10.1088/1748-9326/aba660.
24. Unruh, G.C. (2019). The Real Stranded Assets of Carbon Lock-In. One Earth *1*, 399–401. https://doi.org/10.1016/j.oneear.2019.11.012.
25. McCollum, D.L., Zhou, W., Bertram, C., de Boer, H.-S., Bosetti, V., Busch, S., Després, J., Drouet, L., Emmerling, J., Fay, M., et al. (2018). Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. Nat. Energy *3*, 589–599. https://doi.org/10.1038/s41560-018-0179-z.
26. Seto, K.C., Davis, S.J., Mitchell, R.B., Stokes, E.C., Unruh, G., and Ürge-Vorsatz, D. (2016). Carbon Lock-In: Types, Causes, and Policy Implications. Annu. Rev. Environ. Resour. *41*, 425–452. https://doi.org/10.1146/annurev-environ-110615-085934.
27. Zhou, W., McCollum, D.L., Fricko, O., Fujimori, S., Gidden, M., Guo, F., Hasegawa, T., Huang, H., Huppmann, D., Krey, V., Liu, C., Parkinson, S., Riahi, K., Rafaj, P., Schoepp, W., Yang, F., and Zhou, Y. (2020). Decarbonization pathways and energy investment needs for developing Asia in line with 'well below' 2°C. Clim. Pol. *20*, 234–245. https://doi.org/10.1080/14693062.2020.1722606.
28. Jakob, M., Steckel, J.C., Jotzo, F., Sovacool, B.K., Cornelsen, L., Chandra, R., Edenhofer, O., Holden, C., Löschel, A., Nace, T., et al. (2020). The future of coal in a carbon-constrained climate. Nat. Clim. Chang. *10*, 704–707. https://doi.org/10.1038/s41558-020-0866-1.
29. Reitzenstein, A., Popp, R., Oei, P.-Y., Hanna, B., Stognief, N., Kemfert, C., Jenny, K., and Wehnert, T. (2022). Structural Change in Coal Regions as a Process of Economic and Social-Ecological Transition - Lessons Learnt from Structural Change Processes in Germany (Dessau-Roslau: Umweltbundesamt). https://www.umweltbundesamt.de/publikationen/structural-change-in-coal-regionsas-a-process-of.
30. Geoscience Australia (2021). Australia's Energy Commodity Resources, 2021 Edition. https://www.ga.gov.au/digital-publication/aecr2021/coal.

31. Meinshausen, M. (2015). Individual Report to the Land Court of Queensland on "Climate Change – Emissions". http://envlaw.com.au/wp-content/uploads/carmichael16.pdf.

32. Buckley, T., and Tom, S. (2013). Remote Prospects - A Financial Analysis of Adani's Coal Gamble in Australia's Galilee Basin (The Institute for Energy Economics and Financial Analysis (IEEFA)).

33. Buckley, T., and Nicholas, S. (2017). Adani: Remote Prospects - Carmichael Status Update 2017 (The Institute for Energy Economics and Financial Analysis (IEEFA)). https://ieefa.org/wp-content/uploads/2017/04/Adani-Remote-Prospects-Carmichael-Status-Update-2017_April-2017_SN.pdf.

34. Quiggin, J. (2017). The Economic (Non)viability of the Adani Galilee Basin Project (The Australia Institute). https://australiainstitute.org.au/wp-content/uploads/2020/12/The-economic-non-viability-of-the-Adani-Galilee-Basin-Project.pdf.

35. Holz, F., Haftendorn, C., Mendelevitch, R., and von Hirschhausen, C. (2016). A Model of the International Steam Coal Market (COALMOD-World). Data Documentation*85* (DIW Berlin, German Institute for Economic Research). https://www.diw.de/documents/publikationen/73/diw_01.c.546364.de/diw_datadoc_2016-085.pdf.

36. International Energy Agency (2019). Coal Information 2019 (OECD/IEA). https://doi.org/10.1787/4a69d8c8-en.

37. IEA (2021). World Energy Outlook 2021 (International Energy Agency).

38. — (2016). World – Coal Supply. [Online; accessed 2022-08-03]. 10.1787/data-00465-en.

39. Global Energy Monitor (2021). Global Coal Plant Tracker. https://globalenergymonitor.org/projects/global-coal-plant-tracker/summary-tables/.

40. IPCC (2018). Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (IPCC). https://www.ipcc.ch/sr15/download/.

41. International Energy Agency (2019). World Energy Outlook 2019 (International Energy Agency).

42. Christoff, P. (2022). Mining a fractured landscape: The political economy of coal in Australia. In The Political Economy of Coal, J. Michael and Steckel., eds. (Routledge), pp. 233–257. https://doi.org/10.4324/9781003044543-17.

43. Rosewarne, S. (2016). The transnationalisation of the Indian coal economy and the Australian political economy: The fusion of regimes of accumulation? Energy Pol. *99*, 214–223. https://doi.org/10.1016/j.enpol.2016.05.022.

44. Stutzer, R., Rinscheid, A., Oliveira, T.D., Loureiro, P.M., Kachi, A., and Duygan, M. (2021). Black coal, thin ice: the discursive legitimisation of Australian coal in the age of climate change. Humanit. Soc. Sci. Commun. *8*, 178. https://doi.org/10.1057/s41599-021-00827-5.

45. Curran, G. (2021). Coal, climate and change: The narrative drivers of Australia's coal economy. Energy Res. Social Sci. *74*, 101955. https://doi.org/10.1016/j.erss.2021.101955.

46. Baer, H.A. (2016). The nexus of the coal industry and the state in Australia: Historical dimensions and contemporary challenges. Energy Pol. *99*, 194–202.

47. Curran, G. (2020). Divestment, energy incumbency and the global political economy of energy transition: the case of Adani's Carmichael mine in Australia. Clim. Pol. *20*, 949–962. https://doi.org/10.1080/14693062.2020.1756731.

48. Buckley, T. (2019). Billionaire Adani Being Subsidised for Carmichael Thermal Coal Mine (The Institute for Energy Economics and Financial Analysis (IEEFA)). https://ieefa.org/wp-content/uploads/2019/08/IEEFA-Note_Billionaire-Adani-Being-Subsidised-for-Carmichael-Thermal-Coal-Mine_29-August-2019.pdf.

49. Tate, D., Ryan, C.S., and Matikinca, A. (2021). Deep Trouble - Tracking Global Coal Mine Proposals (Global Energy Monitor/Oxpeckers). https://globalenergymonitor.org/report/deep-trouble-tracking-global-coalmine-proposals/.

50. Lewis, C., Aitkenhead, B., Gasson, B., Gibbons, M., Nash, A., O'Seighin, C., Nguyen, T., and Smith, S. (2021). Resources and Energy Major Projects: 2021 (Australian Government: Department of Industry, Science, Energy and Resources). https://www.industry.gov.au/data-and-publications/resources-andenergy-major-projects-2021.

51. Campbell, R., and Carter, L. (2021). Mind the Gaps (The Australia Institute). https://australiainstitute.org.au/report/mind-the-gaps/.

52. Caldecott, B., James, T., and Ma, Y. (2013). Stranded Down under? Environment-related Factors Changing China's Demand for Coal and what This Means for Australian Coal Assets (University of Oxford, Smith School of Enterprise and the Environment). https://www.smithschool.ox.ac.uk/sites/default/files/2022-03/stranded-down-under-report.pdf.

53. Mercure, J.-F., Pollitt, H., Viñuales, J.E., Edwards, N.R., Holden, P.B., Chewpreecha, U., Salas, P., Sognnaes, I., Lam, A., and Knobloch, F. (2018). Macroeconomic impact of stranded fossil fuel assets. Nat. Clim. Chang. *8*, 588–593. https://doi.org/10.1038/s41558-018-0182-1.

54. Yanguas-Parra, P.A., Malz, N., Oei, P.Y., Furnaro, A., Hauenstein, C., Quiceno, G., Corral-Montoya, F., Mitterecker, T., Hanto, J., and Hanto, J. (2023). Perspective: How a short-term relapse to coal could put exporting countries and just transition processes at risk. Energy Res. Social Sci. *97*, 102989. https://doi.org/10.1016/j.erss.2023.102989.

55. International Energy Agency (2022). World Energy Outlook 2022 (World Energy Outlook. OECD). https://doi.org/10.1787/3a469970-en.

56. Pai, S., Emmerling, J., Drouet, L., Zerriffi, H., and Jewell, J. (2021). Meeting well-below 2°C target would increase energy sector jobs globally. One Earth *4*, 1026–1036. https://doi.org/10.1016/j.oneear.2021.06.005.

57. Richter, P.M., Mendelevitch, R., and Frank, J. (2018). Coal taxes as supply-side climate policy: a rationale for major exporters? Climatic Change *150*, 43–56. https://doi.org/10.1007/s10584-018-2163-9.

58. Hauenstein, C. (2022). COALMOD-world v2.0 (Zenodo). https://doi.org/10.5281/zenodo.7077678.

59. Hauenstein, C., Holz, F., Rathje, L., and Mitterecker, T. (2023). COALMOD-World 2.0 Data, Results, Figures for: Stranded Assets in the Coal Export Industry? the Case of the Australian Galilee Basin (Zenodo). https://doi.org/10.5281/zenodo.7534651.

60. Cassotta, S., Cueva, V.P., and Raftopoulos, M. (2021). A Case Study of the Carmichael Coal Mine from the Perspectives of Climate Change Litigation and Socio-Economic Factors. Law Environ. Dev. *17*, 55–71. http://www.leadjournal.org/content/a1704.pdf.

61. Maddhi Reddy, P., and Rosencranz, A. (2018). Challenging the Proposed Carmichael Mine Before the UN. Environ. Pol. Law *48*, 31–36. https://doi.org/10.3233/EPL-180047.

62. Australia Institute (2021). The Coal Wars - Fact Check. https://australiainstitute.org.au/wp-content/uploads/2020/12/P303-Coal-hard-facts_0.pdf.

63. Haftendorn, C., and Holz, F. (2010). Modeling and Analysis of the International Steam Coal Trade. Energy J. *31*, 205–230. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol31-No4-10.

64. Trüby, J., and Paulus, M. (2012). Market Structure Scenarios in International Steam Coal Trade. Energy J. *33*. https://doi.org/10.5547/01956574.33.3.4.

65. Gosens, J., Turnbull, A.B.H., and Jotzo, F. (2022). China's decarbonization and energy security plans will reduce seaborne coal imports: Results from an installation-level model. Joule *6*, 782–815. https://doi.org/10.1016/j.joule.2022.03.008.

66. Australian Bureau of Statistics (2016). Australian Statistical Geography Standard (ASGS) Volume 1 - Main Structure and Greater Capital City Statistical Areas. Australian Bureau of Statistics. File: State and Territory (STE) ASGS Ed 2016 Digital Boundaries in ESRI Shapefile Format. https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/1270.0.55.001July%5C%202016?OpenDocument.

67. Office of the Chief Economist (2021). Resources and Energy Quaterly. https://publications.industry.gov.au/publications/resourcesandenergyquarterlymarch2021/documents/Resources-and-Energy-Quarterly-March-2021.pdf.
68. International Energy Agency (2021). OECD – Coal Exports by Destination. https://doi.org/10.1787/data-00463-en.
69. (2021). World – Coal Supply. https://doi.org/10.1787/data-00465-en.
70. Stanway, D., and Cadell, C. (2021). President Xi Says China Will Start Cutting Coal Consumption from 2026 (Reuters). https://www.reuters.com/world/china/chinas-xi-says-china-will-phase-down-coal-consumption-over-2026-2030-2021-04-22/.
71. Argus Media (2021). South Korea approves coal phase-out by 2050. https://www.argusmedia.com/en/news/2267757-south-korea-approves-coal-phaseout-by-2050.
72. Australian Government Department of Industry, Science, Energy and Resources (2021). Australia's Nationally Determined Contribution. Communication 2021. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Australia%20First/Australia%20Nationally%20Determined%20Contribution%20Update%20October%202021%20WEB.pdf.
73. Chinese Government (2021). China's Achievements, New Goals and New Measures for Nationally Determined Contributions. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/China%20First/China%20Achievements,%20New%20Goals%20and%20New%20Measures%20for%20Nationally%20Determined%20Contributions.pdf.
74. BBC News (2021). COP26: India PM Narendra Modi pledges net zero by 2070. https://www.bbc.com/news/world-asia-india-59125143.
75. Japanese Government (2021). Japan's Nationally Determined Contribution (NDC). https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Japan%20First/JAPAN_FIRST%20NDC%20(UPDATED%20SUBMISSION).pdf.
76. The Government of the Republic of Korea (2020). 2050 Carbon Neutral Strategy of the Republic of Korea. Towards a Sustainable and Green Society 2050. https://unfccc.int/sites/default/files/resource/LTS1_RKorea.pdf.
77. Tzu-ti, H. (2021). Taiwan Eyes Net Zero Emissions by 2050 (Taiwan News). https://www.taiwannews.com.tw/en/news/4279634.
78. METI: Ministry of Economy, Trade and Industry (2021). Outline of Strategic Energy Plan. https://www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/6th_outline.pdf.
79. Argus Media (2021). Japan cuts 2030 coal/gas power share targets. https://www.argusmedia.com/en/news/2236379-japan-cuts-2030-coalgas-power-share-targets.
80. Bureau of Energy; MOEA (2018). The Electric Power Supply and Demand Report of Taiwan. https://www.moeaboe.gov.tw/ECW/english/content/wHandMenuFile.ashx?menu_id=8679&file_id=7047.
81. Global Energy Monitor; Sierra Club; CREA; Climate Risk Horizons; GreenID; Ekosfer (2021). Boom and Bust 2021: Tracking the global coal plant pipeline. https://globalenergymonitor.org/report/boom-and-bust-2021-tracking-the-globalcoal-plant-pipeline-2/.
82. Suarez, I., and Gray, R. (2021). With China's Withdrawal from Overseas Coal, the Pipeline for New Coal in Asia Could Drop to 22 GW — All of Which Will Likely Not Be Built (Global Energy Monitor, CREA). https://globalenergymonitor.org/report/with-chinas-withdrawal-from-overseas-coal-the-pipeline-for-new-coal-inasia-could-drop-to-22-gw-all-of-which-will-likely-not-be-built/.
83. He, G., Lin, J., Zhang, Y., Zhang, W., Larangeira, G., Zhang, C., Peng, W., Liu, M., and Yang, F. (2020). Enabling a Rapid and Just Transition away from Coal in China. One Earth *3*, 187–194. https://doi.org/10.1016/j.oneear.2020.07.012.
84. Parra, Y., Paola, G.G., Brecha, R., Hare, B., Schaeffer, M., and Fuentes, U. (2019). Global and Regional Coal Phase-Out Requirements of the Paris Agreement: Insights from the IPCC Special Report on 1.5°C (Climate Analytics).
85. AEMO: Australian Energy Market Operator. 2020 Integrated System Plan. For the National Electricity Market. 2020. https://www.aemo.com.au/-/media/files/major-publications/isp/2020/final-2020-integrated-system-plan.pdf?la=en.
86. International Energy Agency (2020). World Energy Outlook 2020 (International Energy Agency), p. 464. https://doi.org/10.1787/20725302.
87. Yonhap News Agency (2020). S. Korea unveils draft plan to foster renewable energy. https://en.yna.co.kr/view/AEN20200508002200320.
88. Hauenstein, C., and Holz, F. (2021). The U.S. coal sector between shale gas and renewables: Last resort coal exports? Energy Pol. *149*, 112097. https://doi.org/10.1016/j.enpol.2020.112097.
89. Vinichenko, V., Cherp, A., and Jewell, J. (2021). Historical precedents and feasibility of rapid coal and gas decline required for the 1.5°C target. One Earth *4*, 1477–1490. https://doi.org/10.1016/j.oneear.2021.09.012.
90. International Energy Agency (n.d.). OECD iLibrary World Energy Statistics. OECD. https://doi.org/10.1787/enestats-data-en.
91. (2020). Global Energy Review 2020 - the Impacts of the Covid-19 Crisis on Global Energy Demand and CO_2 Emissions. (Paris).
92. Global Energy Review 2021. Paris: International Energy Agency; 2021.
93. Clark, R., Zucker, N., and Urpelainen, J. (2020). The future of coal-fired power generation in Southeast Asia. Renew. Sustain. Energy Rev. *121*, 109650. https://doi.org/10.1016/j.rser.2019.109650.
94. Australian Government Department of Industry, Science, Energy and Resources (2021). Australia's emissions projections 2021. https://www.industry.gov.au/sites/default/files/October%5C%202021/document/australias_emissions_projections_2021_0.pdf.
95. AEMO: Australian Energy Market Operator (2021). Draft 2022 Integrated System Plan. For the National Electricity Market. https://www.aemo.com.au/-/media/files/major-publications/isp/2022/2022-documents/2022-integrated-system-plan-isp.pdf?la=en.