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Stranded Assets in the Coal Export Industry? The Case of the Australian Galilee Basin

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Abstract

Steam coal exporters face increasing uncertainty about future coal demand and risks of asset stranding. Nevertheless, new export-oriented coal mine projects are still brought forward. In this study, we use the coal sector model COALMOD-World to assess the economic prospects of investments in the export-oriented steam coal sector, and in particular of coal mines in the Galilee Basin, Australia. We parameterize coal mining in the Galilee Basin based on the Carmichael coal mine and export project specifics. We construct three coal demand scenarios with varying climate policy ambitions based on bottom-up coal sector data of the major coal consuming countries in Asia. We find that, even under most optimistic assumptions, new coal mines in the Galilee Basin are not economically viable in the long-run and prone to become stranded assets. In other Australian basins only very limited investments are required in the most conservative demand scenarios and only to replace exhausted coal mining capacities. Australian steam coal production decreases significantly in all scenarios due to down-phasing domestic demand and shrinking export opportunities. Investments in other world regions are only viable in the most conservative demand scenario. Any new investments in steam coal supply in Australia and globally, and particularly in export-oriented coal supply, are at risk of becoming stranded assets.

Keywords— coal, investments, international coal trade, stranded assets, numerical modeling, scenarios, Galilee Basin, Australia, Asia

JEL Codes— Q31, Q37, Q47, L72, C61

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1 Introduction

Limiting global warming to 1.5°C of pre-industrial levels requires the rapid decline of coal use over the next decades (IPCC 2018). The climate conference COP26 in Glasgow in November 2021 has heralded the end of coal in the next decades as political objective. However, the late end date leaves room for different interpretations by coal suppliers and consumers as to the trajectory in the very next years.

Indeed, the coal industry does not seem ready to comply with climate targets. According to Global Energy Monitor (2022), there are proposals for new steam coal mining projects with a cumulative capacity of some 1300 million tons per annum (Mtpa).¹ Some 380 Mtpa of these planned capacities are expansion projects, but almost 900 Mtpa are in greenfield projects. About 2/3 of the proposed capacities are in Australia, China, and India. These mining expansion plans reflect that coal demand, in particular in Asia, is expected to remain high for the next decades (Chen and Mauzerall 2021; Global Energy Monitor et al. 2021). Australia, one of the major coal exporting countries (IEA 2020a), is one example of a country that so far has shown little intention to reduce coal production, but rather plans to continue exporting large coal quantities over the next decades (SEI et al. 2021).

However, investments in coal supply capacities are at risk of becoming stranded if not aligned with climate targets (Ploeg and Rezai 2020). McGlade and Ekins (2015) and Welsby et al. (2021) find that Australia will have to leave the overwhelming majority of its coal reserves in the ground if the world is to limit global warming to 2°C or 1.5°, respectively. They find 93-95 % unburnable coal reserves in Australia until 2050 which is in the same range as the stranded coal reserves of the other two high-profile exporters that are losing their markets, the USA and Russia (Former Soviet Union). Of Australia’s existing coal mining capacities, around half would have to remain unused in scenarios with ambitious climate policies (Hauenstein 2022). Even though Auger et al. (2021) assume less stringent climate policy, they also find that Australia risks to see around 140 Mtpa of yearly capacity – a third of today’s capacity – as stranded. Australia will be among the hardest hit coal exporters, next to the United States. Caldecott, Tilbury, and Ma (2013) point out the particularly high risk of stranding for greenfield coal projects in Australia if the industries’ expectations for a continuously high coal demand growth in China do not materialize.

Despite the risk of asset stranding, the Australian government has continued to support coal and to forecast further increase in Australian coal production (Christoff 2022; Stutzer et al. 2021; SEI et al. 2021). This perpetuation of the coal lock-in increases the risk for asset stranding (Unruh 2019). Taking into account the large share of the national workforce in the coal sector, SEI et al. (2020) apprehend difficulties for Australia to accomplish a just transition. Australian coal miners are at risk of losing their jobs even in moderately ambitious climate policy scenarios (Auger et al. 2021). However, Mercure et al. (2018) show that Australia might actually gain in total in terms of cumulative GDP in a 2°C scenario compared to a high fossil fuel consumption scenario, whereby losses (stranding) of cumulative fossil fuel value in the country would be outweighed by gains in other sectors.

¹In this paper, we use the term steam coal to denominate thermal coal. This includes mostly bituminous coals, but also sub-bituminous coals from Indonesia. We exclude lignite from our analysis.

In this context, we assess the economic viability of the famous Carmichael project by Adani in the Galilee Basin. We use this notorious project to study the economic prospects of investments in the export oriented steam coal sector today and their risk of becoming stranded assets.

The Galilee Basin is a steam coal basin in central Queensland in Northeastern Australia and until recently was one of the world's largest known untapped coal basins (Geoscience Australia 2021). With rising coal prices in the 2000s, interest in this remote basin increased and a number of coal mine projects were announced, one of them the Carmichael Coal Mine and Rail Project, with an initially proposed coal production capacity of 60 Million tons per year (Mtpa) (DAWE 2018). With this size, it would have been one of the largest coal mines of the world. Developed by a subsidiary of the Indian Adani Group, Adani Mining/Bravus Mining,² it was supposed to boost coal supply for growing Indian coal demand, and supported by the Indian government's economic development program (Rosewarne 2016). Support has also come from the federal Australian and the regional state government of Queensland, which have been intertwined with the domestic coal industry for many decades (Baer 2016). Carmichael is be the first mine developed in the Galilee Basin and could possibly pave the way for other mining projects in the basin.

However, the Carmichael project's economic viability has been questioned ever since its development started in 2010. On a global level, long periods of low steam coal prices, growing global efforts to reduce greenhouse gas emissions, as well as unfavourable physical conditions have put a question mark on the project's viability (Buckley and Sanzillo 2013; Buckley 2015; Buckley 2017; Quiggin 2017). By 2021, over 40 financial institutes and banks, including major international investment banks, have ruled out financing Adani's mine or the Abbot Point coal terminal. Due to the economic challenges and difficulties to acquire sufficient funding, the project was downsized several times and, as of early 2022, envisages an initial production capacity of 10 Mtpa. Beyond economic doubts, Carmichael and the Galilee Basin projects have been criticized for their potentially severe environmental impacts, including harmful effects on the Great Barrier Reef, and for being located on indigenous peoples' sacred land (Meinshausen 2015; Foxwell-Norton and Lester 2017).

Despite the criticism, Adani obtained all the required state and federal approvals until 2021 and actually started the construction of the mine in June 2019 and of the rail line in June 2020. After many years of sinking investment expenditures - combined with strong political support in Australia and Queensland - the project is on the verge of starting commercial extraction in 2022. The global post-COVID-19 recovery with unusually high coal prices have turned the project's economics favorable for a moment.

In this paper, we use the partial equilibrium model COALMOD-World of the global steam coal market (Hauenstein 2022; Holz et al. 2016) to assess prospects for coal production from the Galilee Basin and Australia in general. We take into account the Carmichael coal mine specifics, such as geographical location and costs. We address the uncertainty faced by the

²Due to the negative publicity around the Carmichael mine and to weaken the opposition's "Stop Adani" slogan, several subsidiaries of the Adani Group as well as the Adani Abbot Point Terminal changed their names and removed all references to the parent company. Adani Abbot Point Terminal became North Queensland Export Terminal (NQXT); Adani Mining became Bravus Mining; Adani's new coal rail haulage company is now called Bowen Rail Company.

Carmichael project through the lens of three diverging scenarios for global coal demand, focusing particularly on demand in the Asian region. Beyond the Carmichael project and other greenfield coal projects in the Galilee Basin, this is relevant for all Australian steam coal production, which exports large shares of its production (IEA 2020a) and is confronted with declining domestic steam coal demand (AEMO 2020; Jotzo, Mazouz, and Wiseman 2018).

Our results show that, even for very low cost assumptions, the Carmichael project is not economically viable in the long-run. Under none of the assessed scenarios, investments in coal production capacities in the Galilee Basin are made. Australian coal production decreases significantly in all scenarios due to ceasing domestic demand and shrinking export opportunities. Investments in additional coal mining capacities in other Australian basins are only viable in the most conservative demand scenario and only for replacing retiring capacities. However, already in case of moderately more ambitious climate policy in major coal consuming countries, these investments would also be dispensable. Largely the same applies to steam coal supply investments in other world regions. The risk for asset stranding is particularly high for export-oriented coal supply investments, while any coal supply expansions aggravate the competition for remaining market shares and the economically defaulting risk within the entire coal sector.

Our model results are contrasted by current real-world developments, with sales from the Carmichael mine starting in 2022. These might cover some of the sunk investment expenditures made by Adani over more than a decade of project development. This is possible in an unusually high price market, which is due to the uncertainties related to the COVID-19 recovery, the Russian war in Ukraine and flooding in some of Australia’s coal regions, but not likely to perpetuate (IEA 2021b).

In the remainder of this paper, we first provide more background information on the Galilee Basin and the Carmichael project. We then address coal sector developments in the Asian region and introduce our scenario design and the numerical model COALMOD-World. We show and discuss our results in Section 3, before we conclude.

2 Background information and methods

In the first part of this section, we describe the Carmichael project, which we use to characterize coal mining in the Galilee Basin and to derive parameter values for our model. Coal production in Australia crucially depends on importing countries in Asia, so we describe coal demand developments in this region in the second part of this section (2.2). Based on this information we develop three demand scenarios for our model-based analysis. Last, we describe the global coal sector model and how the Galilee Basin and related infrastructure are represented in it (Section 2.3).

2.1 The Carmichael mine in the Galilee Basin in Australia

The Galilee Basin is a steam coal basin in central Queensland in Northeastern Australia. The first significant deposits of hard coal were discovered in the 1970s. Due to the basin’s relative remoteness and lack of mining infrastructure, more precise assessments of the basin’s reserves were conducted only in the 2000s when global coal prices increased and greenfield exploration

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

Parameter	Lower Bound	Upper Bound
Reserves [Mtpa]		2300
Energy content [kcal/kg]		4950
Initial production capacity [Mtpa]		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
Initial rail transport capacity [Mtpa]		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

projects became more popular. To open up the Galilee Basin for coal production, long rail lines across floodplains and farmland have 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, power and mining infrastructure require large upfront investments.

In 2010, Adani’s Carmichael mine’s application process began and since then the project has gone through numerous reviews and project changes. The mine has a predicted lifetime of 60 years and is estimated to produce up to 2.3 billion tonnes of steam coal over its life cycle. It includes up to six open-cut pits, five underground mines, mine processing facilities, and a railway line from the mine to the Abbot Point coal export terminal (Cassotta, Cueva, and Raftopoulos 2021).³

The size of the Carmichael project was downsized several times and most drastically in 2018 after the company had failed to attract external funding. The project’s investment volume was reduced from A\$16.5 billion to A\$2 billion (Hepburn 2021).⁴ These savings were mostly made possible by reducing the mine’s initial production capacity from 60 Mtpa to 10 Mtpa with plans to ramp up production capacity later to 27.5 Mtpa later. In addition to the A\$2 billion invested by Adani itself, the Carmichael mine benefits from subsidies from the Australian and Queensland governments estimated at A\$4.4 billion in total over the 30-year project life time (Buckley 2019b). 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 first coal in early 2022.

Given the possible role model function of the Carmichael mine for other Galilee Basin

³Also see Queensland Gov. (2021b). *Carmichael Coal Mine and Rail Project - Project overview*. URL: <https://www.statedevelopment.qld.gov.au/coordinator-general/assessments-and-approvals/coordinated-projects/completed-projects/carmichael-coal-mine-and-rail-project> (visited on 06/21/2021)

⁴For 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.

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 the 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 can be found in Appendix A; more background information on the Galilee Basin including Carmichael and other coal mine projects can be found in the Supplementary Material.

Let us highlight a few data points. First, the Carmichael coal has a relatively low average energy content of 4950 kcal/kg (net as received, NAR) (Reddy and Rosencranz 2018). This is 17.5% lower than the standard Australian benchmark coal (exports via the Newcastle port) with an average energy content of 6000 kcal/kg (Australia Institute 2021).

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, this data was taken from different stages of the project planning. Generally, the downsizing of the project over time - only developing the easier accessible parts of the mine, the shorter railway line, the expansion of only the existing export terminal - has led to lower investment costs by Mtpa annual capacity.

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 (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 slightly higher than other suppliers to the Asian market. The more realistic upper bound estimates, however, are more expensive than all other major suppliers to the Asian market.

2.2 Coal demand 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 (Office of the Chief Economist 2021). In 2019, almost 90 % of Australia's steam coal exports were shipped to these countries (IEA 2021f; IEA 2021g).

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 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 (IEA 2021g). Large parts of their coal imports have traditionally come from Australia.

⁵Reuters (2021). *President Xi says China will start cutting coal consumption from 2026*. URL: <https://www.reuters.com/world/china/chinas-xi-says-china-will-phase-down-coal-consumption-over-2026-2030-2021-04-22/> (visited on 11/26/2021).

⁶Argus Media (2021a). *Japan cuts 2030 coal/gas power share targets*. URL: <https://www.argusmedia.com/en/news/2236379-japan-cuts-2030-coal-gas-power-share-targets> (visited on 11/26/2021).

Table 2: Overview of main Australian coal importing countries and Australia

	AUS	CHN	IND	JPN	KOR	TWN
Steam coal consumption 2019 (Mtpa) ^a	55	3315	866	141	102	59
Steam coal production 2019 (Mtpa) ^a	271	2970	678	1	1	0
Steam coal imports 2019 (Mtpa) ^a	0	232	183	140	102	60
Imports from Australia 2019 (%) ^b	-	38%	2%	57%	31%	40%
Coal phase out/down schedule ^c	-	peak in 2025	-	-46% (2019-2030)	phase out by 2050	-33% (2019-2025)
Carbon-neutrality target date ^d	2050	2060	2070	2050	2050	2050

^aIEA 2021g.

^b Share of Australian coal in total imports of the respective country. Own calculations with data from IEA 2021f and IEA 2021g.

^cChina: Reuters 2021⁵; Japan: own calculations with data from METI 2021, p. 12 and Argus Media 2021⁶; South Korea: Argus Media 2021⁷; Taiwan: own calculations with data from Bureau of Energy, MOEA 2018, p. 10.

^dAustralia: Australian Government Department of Industry, Science, Energy and Resources 2021a, p. 3; China: Chinese Government 2021, p. 2; India: BBC 2021⁸; Japan: Japanese Government 2021, p. 1; South Korea: The Government of the Republic of Korea 2020, pp. 7–8; Taiwan: Taiwan News 2021⁹.

While coal continues to be a major energy source in many Asian countries, the coal sector has come under increased pressure also in these countries due to cheaper alternative power sources, as well as ratcheted up environmental and climate targets (cf. IEA 2021b; Littlecott et al. 2021; Yanguas Parra, Hauenstein, and Oei 2021). Globally, the 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 (Jones, Graham, and Tunbridge 2020).

Since a record high number in 2015, commissioning of new coal capacity has recently dropped to a low level not seen since 2005 (Global Energy Monitor et al. 2021, p. 6). Global coal power capacity under development has declined by about 1,000 GW, or 66 %, between 2015 and 2020, while in the same time around 1,000 GW of planned coal capacity additions were cancelled (Global Energy Monitor et al. 2021, p. 7). And this trend has continued dynamically in 2021.

⁷Argus Media (2021c). *South Korea approves coal phase-out by 2050*. URL: <https://www.argusmedia.com/en/news/2267757-south-korea-approves-coal-phaseout-by-2050> (visited on 11/26/2021).

⁸BBC (2021). *COP26: India PM Narendra Modi pledges net zero by 2070*. URL: <https://www.bbc.com/news/world-asia-india-59125143> (visited on 11/25/2021).

⁹Taiwan News (Aug. 31, 2021). *Taiwan eyes net zero emissions by 2050*. Taiwan News. Section: Environment. URL: <https://www.taiwannews.com.tw/en/news/4279634> (visited on 11/25/2021).

Around COP26 in late 2021, China, 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 of planned new coal capacities in Asia outside of China and India by end 2021 (not considering projects already under construction), if all formerly Chinese finance backed plans are cancelled. And of these remaining planned 22 GW only a minority has secured financing (Suarez and Gray 2021).

With a slowdown of capacity additions, the coal plant fleet is ageing 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 ten to twelve 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 (Global Energy Monitor 2021).

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 entire coal phase-out target (by 2050), while some of the other countries have only set intermediate energy sector targets. Australia and India have not announced any concrete plans to phase out coal combustion. A more detailed description of the steam coal demand and the climate policies in these countries is provided in Appendix B.

CMW coal demand scenarios

Based on the above outlined developments, we design three plausible but diverging global coal demand scenarios which are the aggregate of different national and regional trends (Table 3). The *High demand* scenario, with a continued important role for coal in the 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, Holz, et al. (2022).

We design coal demand pathways for each Asian market as part of the global coal demand scenarios (*High demand* and *Moderate decline*) based on the national coal and energy sector specifics, as well as energy and climate policies. Such "bottom-up" scenarios provide more plausible ranges of coal demand developments by considering physical infrastructure constraints and regional, sector specific developments than do aggregated energy system and general equilibrium models (Hauenstein and Holz 2021). A 1.5°C mitigation scenario requires unprecedented changes of the energy sector in many Asian countries (Vinichenko, Cherp, and Jewell 2021), we therefore rely on IPCC (2018) 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.¹⁰ We, thereby, intend to smooth the short term COVID-19 effect on coal markets in 2020 (IEA 2020c; IEA 2021c).

¹⁰OECD iLibrary World Energy Statistics: https://www.oecd-ilibrary.org/energy/data/iea-world-energy-statistics-and-balances_enestats-data-en (visited on 03/26/2021).

Table 3: Scenario overview

<i>High demand</i>	<i>Moderate decline</i>
Asian countries <ul style="list-style-type: none"> • Assumed lifetime: 40 years (South Korea: 30 years) • Capacity factors: linear reduction to 50% by 2050 (China: 40%), thereafter constant 	Asian countries <ul style="list-style-type: none"> • Assumed lifetime: 25 years • Capacity factors: linear reduction to 40% by 2030, thereafter constant
Australia <ul style="list-style-type: none"> • Based on AEMO (2020) ISP 2020 Central Scenario 	Australia <ul style="list-style-type: none"> • Based on AEMO (2020) ISP 2020 Fast Change Scenario
Rest of the world <ul style="list-style-type: none"> • Based on IEA (2020f) WEO 2020 STEPS 	Rest of the world <ul style="list-style-type: none"> • Based on IEA (2020f) WEO 2020 SDS

1.5°C

Based on IPCC (2018) 1.5°C mitigation scenarios analyzed by Yanguas Parra, Ganti, et al. (2019)

- Median unabated coal consumption of 1.5°C scenarios fulfilling additional sustainability criteria (no/limited temperature overshoot; limited BECCS and carbon uptake from AFOLU)
-

In the *High demand* and *Moderate decline* scenario we calculate future steam coal generation capacity in Asian countries¹¹ based on unit-level coal-fired power plant data from the Global Coal Plant Tracker (Global Energy Monitor 2021). 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 under construction we assume retirement after 40 years of operation¹² (*High demand*), the conservative benchmark used also by Clark, Zucker, and Urpelainen (2020) and Global Energy Monitor et al. (2021), or after 25 years of operation (*Moderate decline*), 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.

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 2050¹³, remaining constant thereafter. 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

¹¹Asian countries represented in CMW: Bangladesh, China, Indonesia, India, Japan, Malaysia, Pakistan, Philippines, South Korea, Taiwan, Thailand, Vietnam

¹²An exception is South Korea where an average retirement age of 30 years is assumed as this corresponds to the planned operational lifetime in the government’s ‘Basic Plan for Long-term Electricity Supply and Demand’ Yonhap News Agency (2020). *S. Korea unveils draft plan to foster renewable energy*. Yonhap News Agency. Section: Economy Business. URL: <https://en.yna.co.kr/view/AEN20200508002200320> (visited on 01/17/2022).

¹³Except for China where the capacity factor is already below 50 % today and where we assume a linear reduction to 40 % in 2050. For those countries where no current capacity factor is available, a capacity factor of 55% was assumed based on the “Rest of the world” factor from Jones, Graham, and Tunbridge (2020, p. 11)

until 2050.

Figure 1 shows the changes in steam coal demand until 2050 of major importers of Australian steam coal in the different scenarios. The inevitable decline is delayed in China and India due to capacities under construction coming online in the next years and a younger coal plant fleet. In comparison to our *High demand* scenario, the *Moderate decline* and 1.5°C scenario show a much faster decline in steam coal demand.

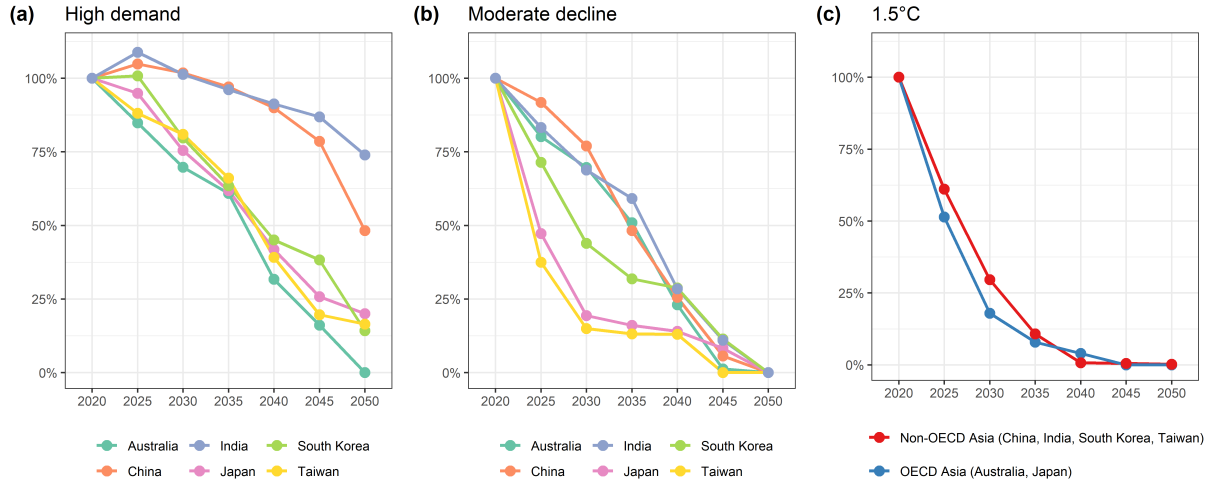


Figure 1: Change in steam coal demand [%] in Japan, China, South Korea, Taiwan and India in the *High demand* (a), *Moderate decline* (b) and 1.5°C scenario (c).

For Australian domestic coal demand we apply scenario data of the 2020 Integrated System Plan (ISP) by AEMO (2020). For the *High demand* 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 have continued the trend linearly to 2050, whereby Australian coal demand will fall to zero in 2050. 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 (AEMO 2020, p. 32). It predicts an almost linear decline of Australian steam coal demand beginning in 2020 and reaching zero by 2045.

For all other countries, we use steam coal demand trend data of the IEA (2020f) "Stated Policies Scenario" (STEPS) for our *High demand*, 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 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 (IEA 2020f, p. 342). 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 (IEA 2020f, p. 343).

We also design a climate policy scenario with an effective coal exit, the 1.5°C scenario. It is based on the IPCC (2018) special report on 1.5°C scenarios. Yanguas Parra, Ganti, et al. (2019) selected those 1.5°C scenarios that also fulfil other sustainability criteria such as reasonably limited use of biomass with CCS (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.

2.3 The COALMOD-World model

COALMOD-World (CMW) is a partial equilibrium model of the world steam coal market (see Hauenstein (2022) for a detailed description of the model version used here and Holz et al. (2016) 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 (see 2.2 for details). 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 (2022). 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 (cf. Haftendorn and Holz 2010; Trüby and Paulus 2012) the steam coal market is modelled as perfectly competitive. The model is calibrated for its starting year 2015. The model can be accessed and downloaded via https://github.com/chauenstein/COALMOD-World_v2.0 and all input and result data files, as well as the code to reproduce the figures, are provided in Hauenstein, Holz, et al. (2022).

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 (2022)). Although not officially announced, China *de facto* restricts the amount of coal imported (IEA 2021b; Gosens, Turnbull, and Jotzo 2022). 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 compared to results by Gosens, Turnbull, and Jotzo (2022) and recent media announcements¹⁴ suggest even lower quotas in future years.

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 2). The dedicated export terminal of the Galilee Basin node is Abbot Point. As described in Section 2.1, the Galilee Basin producer node is parameterized based on Adani’s Carmichael project. In order to analyse 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 data value ranges were assessed in Section 2.1, we use lower end

¹⁴See, for example, Bloomberg News, March 14, 2022: China Seeks to Cut Reliance on Coal Imports With Mining Boom. <https://www.bloomberg.com/news/articles/2022-03-14/china-seeks-to-cut-coal-import-reliance-with-mining-boom> (visited on 03/29/2022)

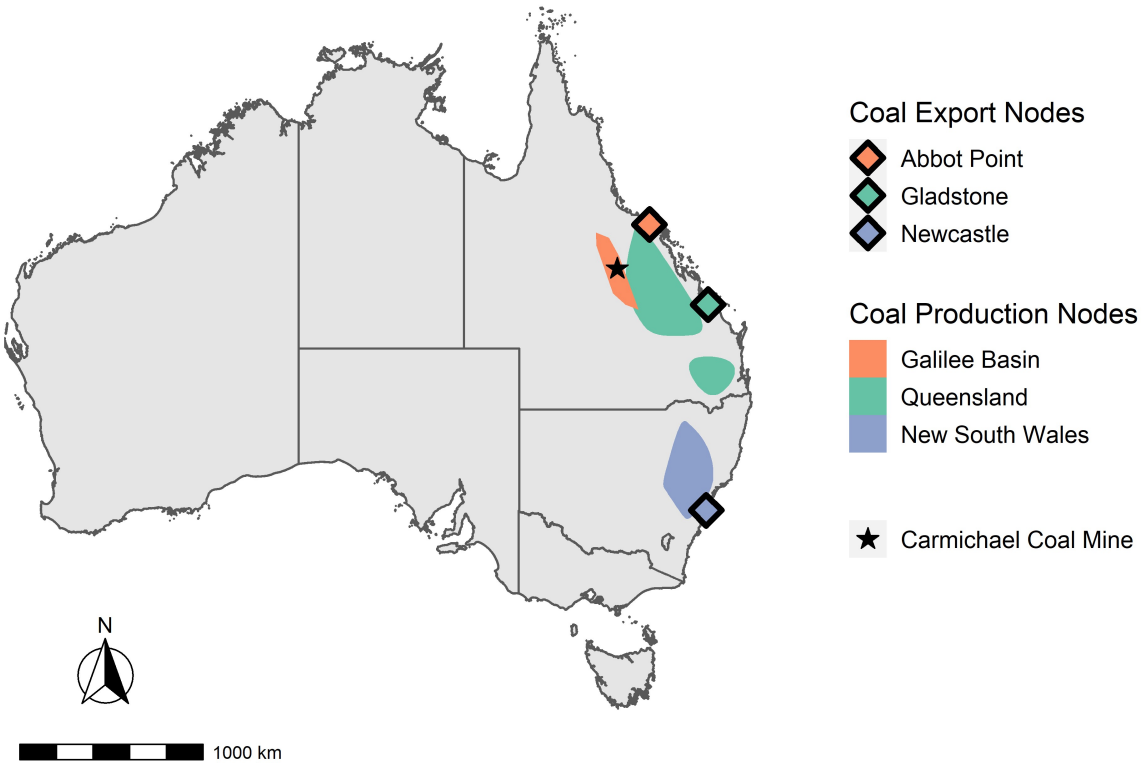


Figure 2: Overview of CMW coal production and export nodes in Australia.

cost estimates and higher end available capacity estimates in order to not underestimate the investment potential in the Galilee Basin.

3 Results and discussion

In this section we present and discuss the results of our model based scenario analysis. We first give insights in consumption and production in the three scenarios that we defined in Section 2.2. We then turn to the prospects of coal investments and asset stranding on the supply side with a particular focus on the Galilee Basin and Australia.

Figure 3 shows global steam coal production and consumption in all three scenarios. While global steam coal consumption remains flat until 2025 in the *High demand* scenario and then starts to decrease, it falls significantly from 2020 on in the scenarios *Moderate decline* and *1.5°C*. However, even in the most conservative scenario, the *High demand*, global steam coal consumption more than halves by 2050 compared to 2020. Only a few countries, including China, India, Indonesia, still see an increase of domestic coal demand between 2020 and 2025. From 2025 on, coal demand also declines in these countries. In the *Moderate decline* scenario, global steam coal demand reduces almost linearly to zero between 2020 and 2050. In case of stringent global climate policies (*1.5°C* scenario), an almost complete global coal phase-out is achieved already in 2040. In this case, global steam coal demand in 2030 is only a quarter of the 2020 level.

Major countries' coal consumption in the *High demand* scenario resembles the trends in the

IEA (2021h) World Energy Outlook 2021 'STEPS' scenario. Only in India consumption starts to decline earlier than in 'STEPS'. By 2050, *High demand* has somewhat lower global coal demand levels than 'STEPS' because many power plants reach their retirement age between 2045 and 2050, which leads to a sharp decline in coal demand.

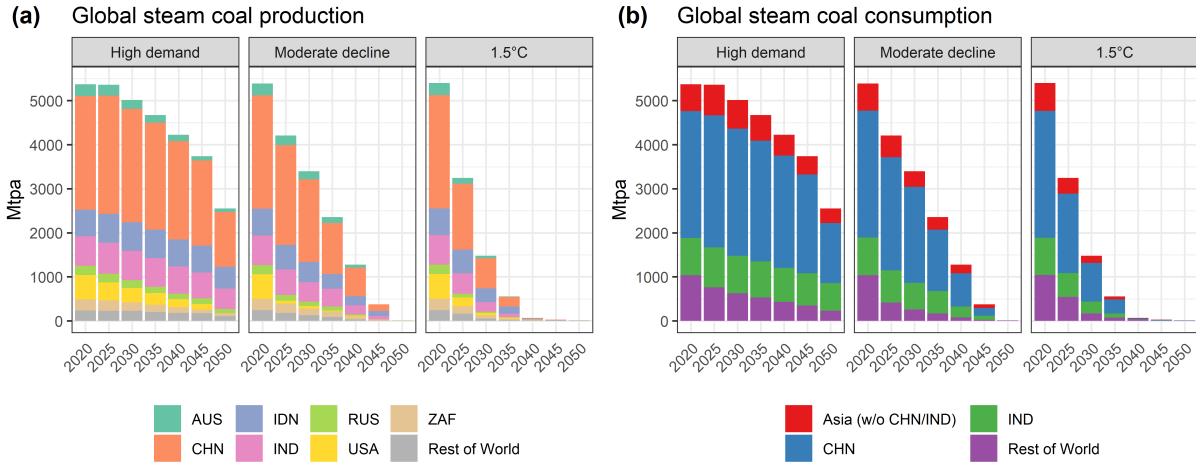


Figure 3: Global steam coal production (a) and consumption (b) in all scenarios in Mt per year.

Note: In (a): AUS = Australia; CHN = China; IDN = Indonesia; IND = India; RUS = Russia; USA = United States of America; ZAF = South Africa; Rest of World = Colombia, Kazakhstan, Mongolia, Mozambique, and Poland.

In (b): Asia (w/o CHN/IND) = Bangladesh, Indonesia, Japan, Malaysia, Pakistan, Philippines, South Korea, Taiwan, Thailand, and Vietnam; CHN = China; IND = India; Rest of World = Australia, Belgium, Brazil, Canada, Chile, Denmark, Finland, France, Germany, Israel, Italy, Kazakhstan, Mexico, Morocco, Netherlands, Poland, Portugal, Russia, South Africa, Spain, Turkey, United Kingdom, and United States of America.

Due to falling global demand also coal production starts to decline no later than 2025. In the *High demand* scenario this decline is felt differently among the major coal producers. While particularly China, India, and Indonesia continue to produce at an only slightly declining level throughout 2040, production in most other major coal producing and exporting countries declines by 1/3 to 2/3 between 2020 and 2040. Yet, these are still high levels compared to the drop in the *Moderate decline* scenario, which would result in global production declining by more than 3/4 between 2020 and 2040, affecting all producers.

This ambiguity is also reflected in the investments in coal production capacities. In the *Moderate decline* scenario, only some minor investments (total: 100 Mtpa) are required in China, while existing production capacities in all other countries are sufficient to cater for the remaining demand (compare Figure 11 in Appendix D). In contrast, in the *High demand* scenario investments into new production capacities would be economic in most major producing countries (2020-2050 total: 3000 Mtpa). However, only in China, India, and Indonesia total mine capacity would be slightly expanded until 2025. Investments in all other major coal exporting countries would provide only replacement of retired capacities.

Thus, considering the high uncertainty of coal demand developments, the risk of asset stranding for new coal mine projects, greenfield and brownfield, is substantial in all countries. This finding is in line with other research that points out the increasing risk of stranding for fossil

fuel supply assets (cf. Auger et al. 2021; Caldecott, Tilbury, and Ma 2013; Mercure et al. 2018; Welsby et al. 2021). In the following, we investigate in more detail to what extent the Galilee Basin projects and Australian production are subject to these uncertain global trends, and what this implies for coal supply investments and the risk of asset stranding in this sector.

3.1 Carmichael: Not a profitable venture

We start analyzing the economic viability of Adani’s Carmichael mine using the most conservative demand scenario, the *High demand*. First we use the lower bound cost estimates of the Carmichael project to parameterize the Galilee Basin producer node, the exporter node representing the Abbot Point Terminal, and the transportation infrastructure between these two nodes (Section 2.1).

Despite this ”pro-investment” configuration and the high-demand scenario in Asian import countries, no investments into production capacity at the Galilee Basin production node are triggered. Only if we reduced the lower bound investment cost estimates (incl. production, railway, and export harbor capacity) significantly further, would production in the Galilee Basin start (compare Figure 8 in Appendix D). Cost reductions of up to 25% do not trigger any investment in production capacity; a reduction of 30% leads to an investment into 19 Mtpa production capacity (becoming available in 2025). But these are hypothetical cost reductions to already questionable low cost estimates.

Yet, contradicting our modeling results, production at the Carmichael mine actually started in the winter 2021/22.¹⁵ To shed light on this new situation, we compare our results to sensitivity model runs where we assume a ”sunk investment” of 10 Mtpa production capacity, i.e. 10 Mtpa production capacity are available without investment expenditures in production capacity needed (see Figure 4).¹⁶ For these sensitivity runs we differentiate between the low and the high production cost estimates (see Table 1). In case of the low production cost estimate, the 10 Mtpa available mining capacity produces at full capacity in both the *High demand* and *Moderate decline* scenario. However, if production costs are high, the available capacity is producing only in the *High demand* scenario. In the other scenarios, the mine, although available, is not used.

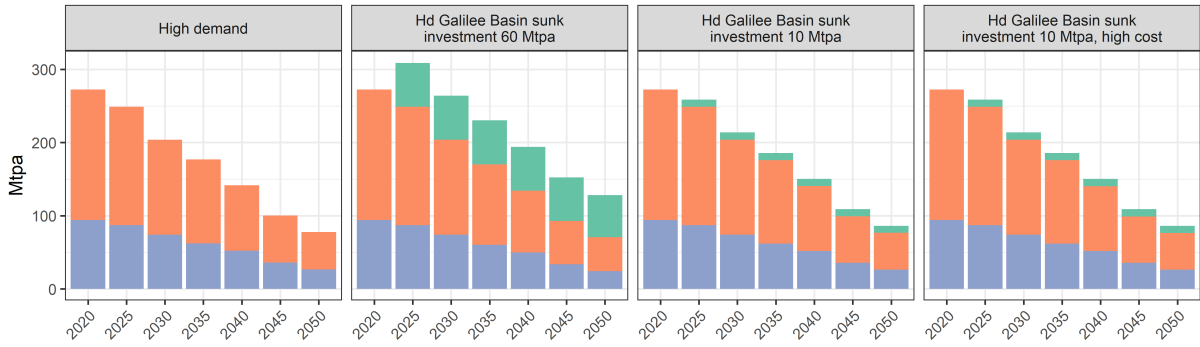
Several arguments suggest that actual costs to produce coal from the Galilee Basin are rather closer the upper end of the parameter ranges stated in Section 2.1 (Table 1). For example, the lower bound of the unit investment cost for new production capacity, as well as production cost estimates are based on the assumption that Carmichael can achieve cost advantages due to economics of scale in the very large capacity configuration (60 Mtpa) that has been abandoned in the last years. In other words, with realistic cost estimates, there is even less economic rationale for production in the Galilee Basin than in the low cost results just shown.

Figure 4 also shows the results for a hypothetical case of 60 Mtpa (i.e., the initially planned

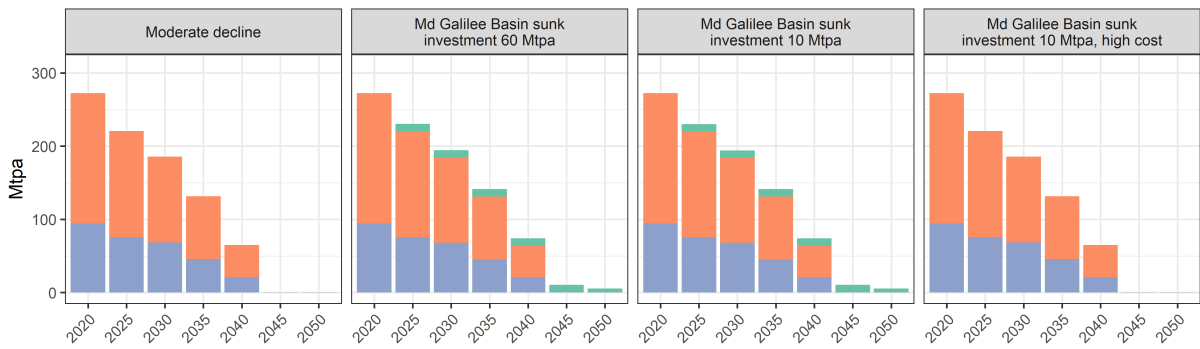
¹⁵Katrina Beavan (2021). *Adani’s first Carmichael Mine coal export shipment imminent after years of campaigns against it*. URL: <https://www.abc.net.au/news/rural/2021-12-29/adani-ships-first-coal/100729834> (visited on 01/05/2022)

¹⁶The sunk investment was implemented as an existing production capacity of 10 Mtpa (and 60 Mtpa, respectively) in the Galilee Basin production node, however, requiring investments in the transportation infrastructure to the port. With additional investments only allowed from 2020 on, a complete supply chain could only be available from 2025 (the next time step in the model) on.

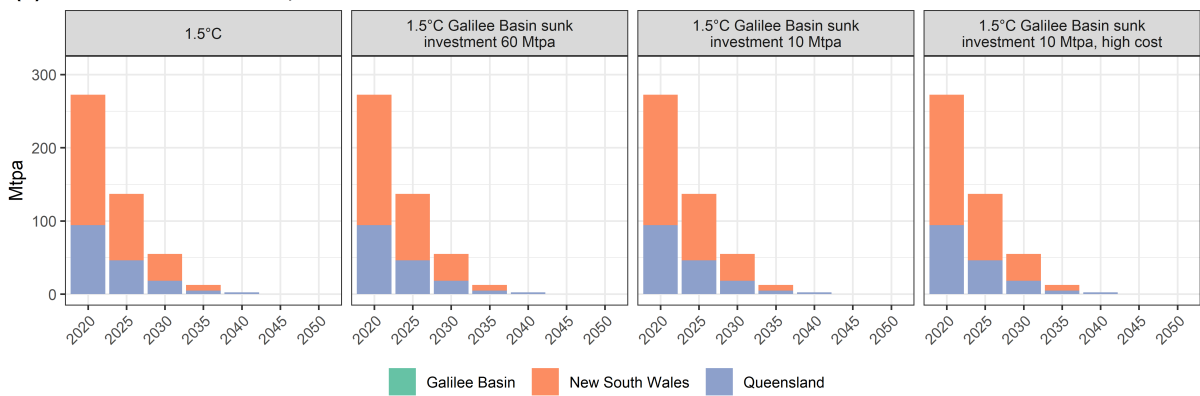
(a) Australian steam coal production: High demand



(b) Australian steam coal production: Moderate decline



(c) Australian steam coal production: 1.5°C



Galilee Basin New South Wales Queensland

Figure 4: Australian steam coal production for different assumptions for the Galilee Basin under the *High demand* (Hd, panel a), *Moderate decline* (Md, panel b) and *1.5°C* scenario (panel c).

capacity of the Carmichael mine) available production capacity in the Galilee Basin (i.e. without investment expenditures needed). While fully used in the *High demand* scenario, less than 20 % of the capacity is used in the *Moderate decline* scenario. Interestingly, Galilee Basin coal hardly affects the global trade flows and volumes, not even in the *High demand* scenario, and does not displace other Australian exports from Queensland or New South Wales. Cumulative global consumption would increase by 0.4 percent in the *High demand* demand scenario between 2025 and 2050 in the case of 60 Mtpa available production capacity, with marginally higher consumption in Japan, South Korea, and India. However, robustness of this effect would have to be tested further, considering potential adjustments in the medium to long-term of importing countries' willingness to pay based on such a long-term change in supply.

Based on these results, it appears highly implausible that operations in the Galilee Basin can be run profitably, even if ignoring the recovery of already accrued investment costs. In other words, chances are high that even the downsized Carmichael project ends up as stranded asset. The decision to continue the development of the Carmichael mine was apparently rather a political decision (Stutzer et al. 2021; Christoff 2022), not an economically driven one.

Considering the bleak economic prospects for the Carmichael mine, it is more than doubtful if 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 other Australian coal basins (Driskell Tate, Shearer, and Matikinca 2021). These projects differ from the ones in the Galilee Basin because they are in already developed basins and require less investments into transportation infrastructure etc. In the next section, we assess the prospects of steam coal production and investments in the rest of Queensland (excluding Galilee Basin) and New South Wales, the two states which together make up for almost all steam coal production in Australia.

3.2 Australian supply and investments on a downward trend

Australian steam coal production has already peaked in all three scenarios and will fall significantly below the current production level by 2025 (Figure 5, panel (a)). In the *Moderate decline* and the $1.5^{\circ}C$ scenario, Australian steam coal production ends within the next two decades, namely by 2045 (*Moderate decline*) or 2040 ($1.5^{\circ}C$). In the *High demand* scenario, Australian production nearly linearly declines from 2020 to about 30% of its 2020 level by 2050.

Australian domestic steam coal demand declines sharply in all three scenarios, further reducing demand for Australian coal (also see Figure 9 in Appendix D). An accelerated decline in domestic coal demand can be expected since the Australian government announced in the fall of 2021 to shut down some 5 GW of coal-fired power capacity even before their originally planned shut down date (Australian Government Department of Industry, Science, Energy and Resources 2021b, p. 19). The draft of the latest 2022 AEMO Integrated System Plan also assumes a much faster decline in Australian coal demand than was estimated in the previous report, which forms the basis of our scenarios (see Section 2.2). The path considered as "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 (AEMO 2021).

The trend in Australian production is mirrored by the trend in Australian exports (Figure

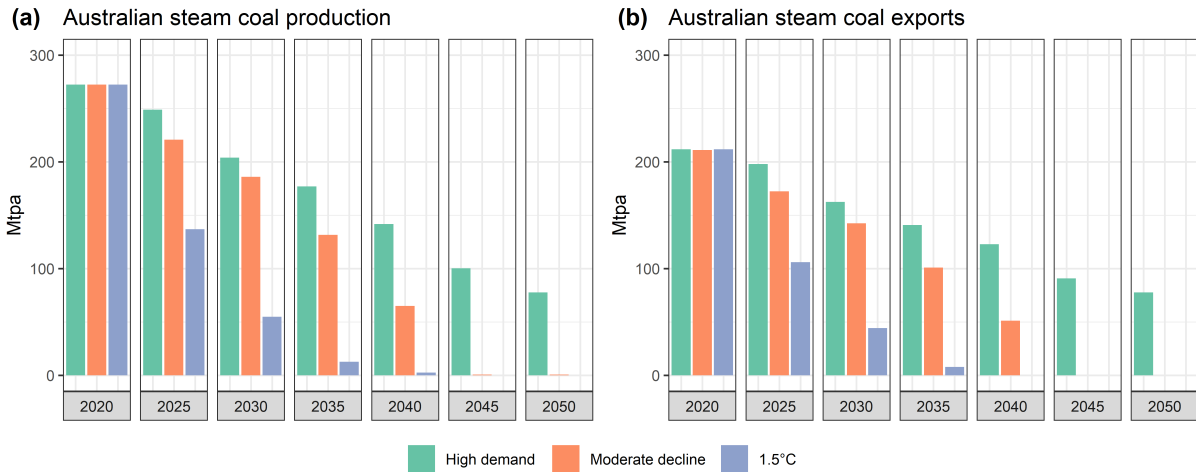


Figure 5: Australian steam coal production (a) and exports (b) in all scenarios in Mt per year.

5, panel (b)), 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 (IEA 2019). The total export share remains at these high level throughout the entire period in all three scenarios.

The vast majority of global and Australian steam coal trade is destined for Asia (Figure 6). The global trend towards Asia is amplified in future years in all scenarios. Australian steam coal exports go almost completely to East Asia, including China, which does not change much over time.¹⁷ 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.¹⁸ In case these restrictions continued, we would expect a continuous rerouting of trade flows with limited influence on exporters’ production volumes. To test for effects of changes in Chinese and Indian import policies, we implemented various sensitivity runs (for details see Appendix D). Besides Australia, major coal suppliers to China are Russia and the USA in the *High demand* scenario and additionally Colombia in the *Moderate decline* scenario. For more details regarding the proportion of domestic steam coal production and imports in China and other South East Asian countries see Figure 10 in Appendix D.

In the *1.5°C* scenario, global seaborne coal trade is decreasing fast after 2020, ceasing at all towards 2040. Of the major exporting countries, Colombia and the USA are the first to lose their market shares in the Asian market (in 2025) due to the high distance-induced 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.

While investments in new production capacities in the Galilee Basin are not competitive,

¹⁷With the Chinese import quota, enforced as ton constraint in CMW, Australian coal is favored over Indonesian coal due to its higher energy content. Total exports of both countries are barely affected by the Chinese import quota because Indonesian coal can potentially replace Australian coal in Asia. In reality, exports to China will likely be split mainly among Indonesia and Australia.

¹⁸Cissy Zhou and Su-Lin Tan (2022). *China-Australia relations: as demand for coal surges, how long can Beijing keep banning Australian supply?* URL: <https://www.scmp.com/economy/china-economy/article/3147774/china-australia-relations-demand-coal-surges-how-long-can> (visited on 01/05/2022)

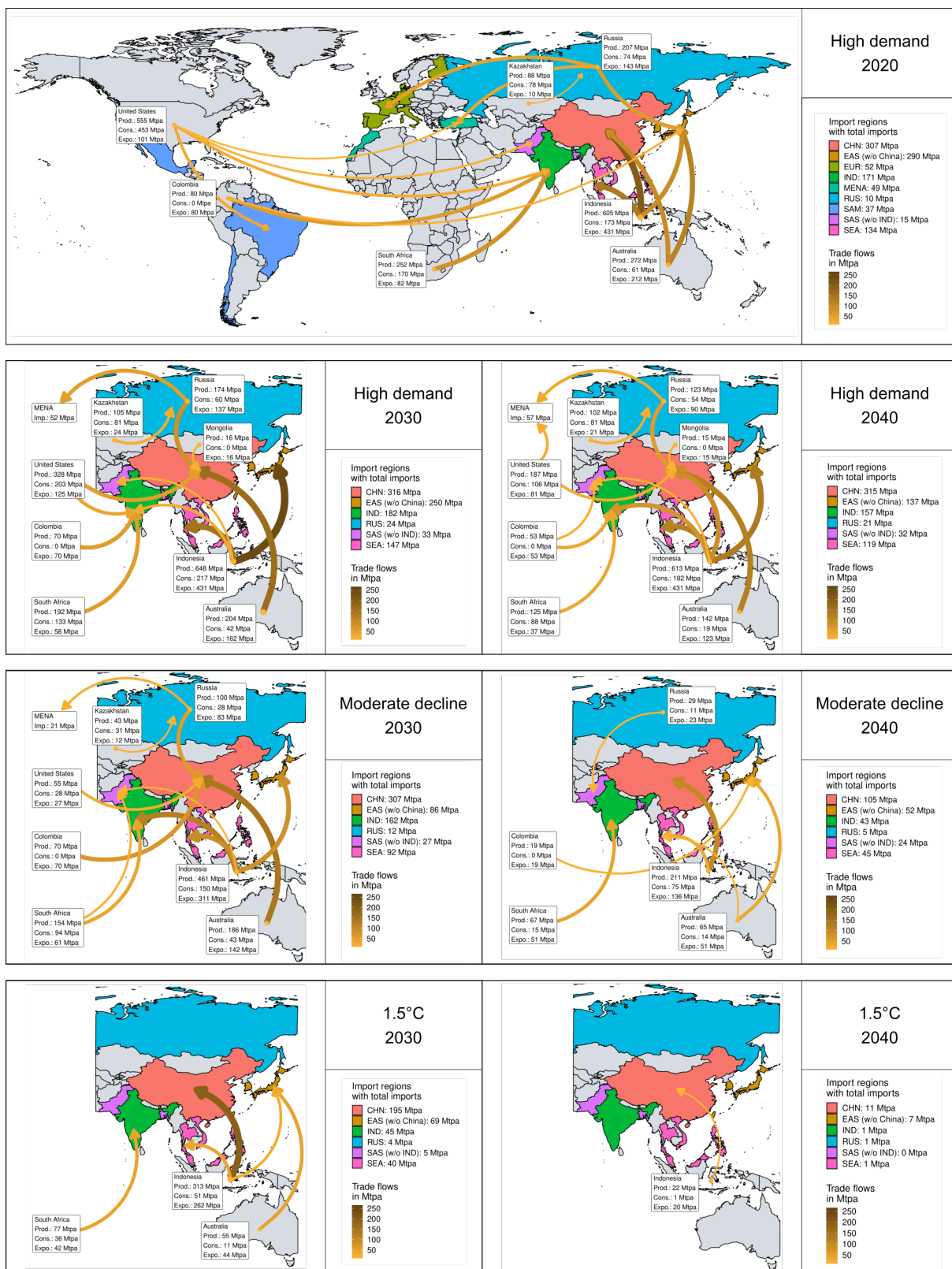


Figure 6: Development of major international steam coal trade flows in Asia-Pacific region 2020-2040, in all scenarios.

the model run for the *High demand* scenario yields investments in some 60 Mtpa production capacity between 2020 and 2050 in the in other Australian coal basins to replace retiring capacities (see Figure 7). Both in Queensland and New South Wales, retirement of mines outpaces new investments, though, 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.

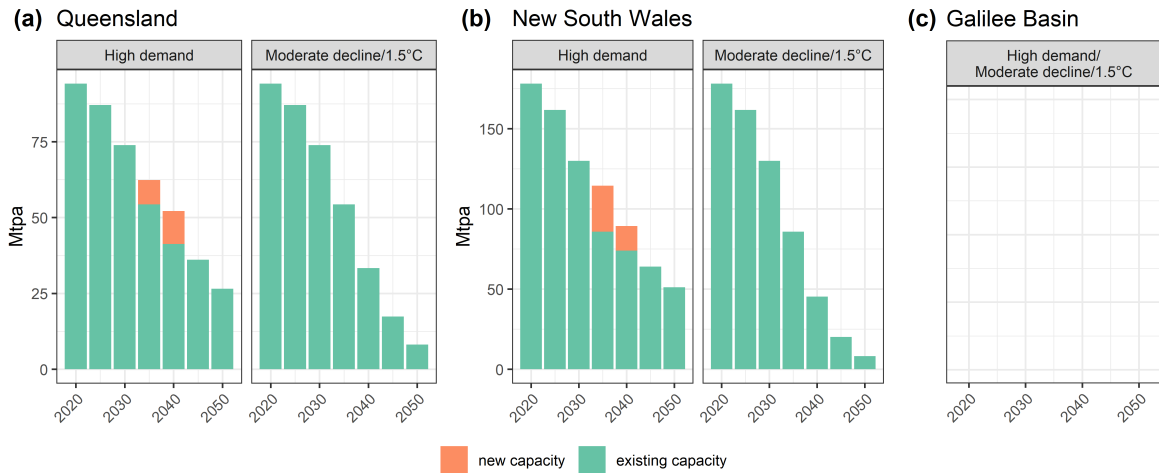


Figure 7: Available steam coal production capacity in Australian CMW producer nodes Queensland (a), New South Wales (b), and Galilee Basin (c), in all three scenarios in Mt per year (2020-2050). 'New capacity' denotes capacity addition (in year a) based on investment in previous model period (year $a - 1$). 'Existing capacity' denotes remaining capacity from previous model periods.

This is in contrast to a large number of proposed production capacity expansions in Australia. As of October 2021, the coal project pipeline in New South Wales and Queensland (excluding 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 of steam and metallurgical greenfield projects are proposed in Queensland (excl. Galilee Basin) and New South Wales.¹⁹ The vast majority of these proposed projects are in an early development stage (IEA 2021b, p. 89).

Furthermore, operating mines in the Hunter Valley - New South Wales' largest coal producing region - are currently operating at less than two thirds (62%) of their approved capacity (Campbell and L. Carter 2021), potentially offering some further leeway before making investments into new capacities profitable. What is more, remaining lifetime of operating coal mines in Australia as reported in Global Energy Monitor 2021 could be underestimating their potential lifetime as the data is mostly based on the duration of governmental permits for operations. In turn, required investments could be overestimated in these cases.

Obviously, any investments in new mining capacities, including brownfield expansions, further weaken the economic viability of existing operations while being strongly exposed to the risk of asset stranding. This applies to Australia, but largely also to all other world regions.

¹⁹Department of Industry, Science, Energy and Resources (2021). *Resources and Energy Major Projects: 2021*. The Australia Institute. URL: <https://www.industry.gov.au/data-and-publications/resources-and-energy-major-projects-2021>.

Considering the potential leeway for continued and even additional coal supply from existing Australian mines, investments into new coal mining capacities appear highly 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 (cf. SEI et al. 2021). Based on their poor economics, the Galilee Basin projects are the most obvious candidates for early scrapping.

4 Conclusions and outlook

In this paper, 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 steam coal sector and Australian coal production. We find that the Carmichael project in Australia's Galilee Basin is not economically viable. Even if already made investments are considered as sunk, profitable long-run operation of the available capacity is highly uncertain. We have shown that, in addition to the poor economics on the supply side, there is no long-run demand for additional coal due to 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 room for additional investments in coal mining capacities. Ratcheting up of climate policies and regulations in line with decisions at COP26 in Glasgow in 2021 would erase the economic ground for any new coal capacities. With such tight expansion potentials, any new coal capacities will exacerbate the risk of asset stranding in the sector.

The Australian government - just as the 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 everything else than a safe bet and come with a high risk of becoming stranded assets. In the wake of international climate commitments, 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 Australia (Auger et al. 2021; Pai et al. 2021), but the right measures early on can help to smooth the transition for affected workers and communities (Jakob et al. 2020; Reitzenstein et al. 2022).

The failure of new greenfield projects shows that coal exporting countries only have a small time window left to earn revenues from coal mining. Richter, Mendelevitich, and Jotzo (2018) 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. The larger the coalition of coal exporters pursuing such a policy, the more sizeable the climate effect.

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 the USA, c.f.

Mendelevitch, Hauenstein, and Holz 2019), including in 2021 in Australia.²⁰ Second, a major caveat of model-based analyses is the limited quality of available data. With the publication of the 'Global Coal Plant Tracker' (Global Energy Monitor 2021), openly accessible data on coal mines has been greatly advanced. However, data on the technical lifetime of existing mines is still scarce. Thus, our results for required coal mine replacement investments have to be considered with some care (compare Hauenstein 2022).

Lastly, the "elephant in the room" is, of course, the question why Adani has moved forward the Carmichael project despite the very high costs and lack of long-term profit prospects. The answer to this question certainly lies in the political economy and also the disconcerting inter-linkage between the coal sector and the political decision-makers in both India and Australia (e.g., Rosewarne 2016). Such political capture of coal projects must be avoided in the future if climate mitigation targets are taken seriously. Transparency on costs, stakeholders and expected externalities is what can help the public to understand the interests and stakes in such a project.

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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.; Visualization, C.H. and T.M.; Funding Acquisition, C.H. and F.H.

Declaration of interests

The authors declare that they have no conflict of interest.

²⁰The Guardian (January 20, 2021): "BHP cuts Mount Arthur coalmine valuation by \$1.5bn after thermal coal price plunges"; <https://www.theguardian.com/business/2021/jan/20/bhp-cuts-mount-arthur-coalmine-valuation-by-15bn-after-thermal-coal-price-plunges>, last accessed April 07, 2022.

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Appendix

A Carmichael project data details

The Galilee Basin is a steam coal basin in central Queensland in Northeastern Australia.²¹ The first significant deposits of hard coal were discovered and identified in the 1970s, but more precise assessments of the Basin’s reserves were conducted only in the 2000s when coal prices increased globally. Today, the basin is estimated to contain a total of 21.2 Gt of hard coal (inferred resources) making it one of the world’s biggest untapped coal basins until recently (Geoscience Australia 2021).

The first company to recognize the basin’s alleged economic potential was GVK Hancock. In 1998 the company applied for a mineral development license to further evaluate its Alpha West project. In the early 2000s several other companies followed and applied for exploration permits for coal (EPC) and mineral development licenses. The major increase in coal exploration activities was driven strongly by the increase in global coal prices during the mid 2000s and was paired with an increased funding from international investors, mainly from China and India (DAWE 2018).

Today, there are ten mining lease applications and three granted mining leases including both open-cut and underground extraction in or overlapping the Galilee Basin. These applications and granted leases belong to seven big coal mining projects (Table 4). Three of the seven projects in an advanced stage of development are owned or partly owned by large Indian energy and infrastructure corporations, Adani Enterprises and GVK. As India has had difficulties in expanding the national coal production, the state-owned Coal India Limited and several energy corporations have started investing in offshore coal projects, backed by the Indian government (Rosewarne 2016).

Table 4: Coal mining leases and coal mining lease applications in the Galilee Basin

Project	Applicant	Planned capacity [Mtpa]	Status
Alpha Coal Project	GVK Hancock	30 ^a	Application
Alpha North Coal Mine Project	Waratah Coal	56 ^b	Application
Carmichael Coal Mine and Rail Project	Adani Mining	60 ^a	Approval
China Stone Coal Project	MacMines Austrasia	38 ^a	Application
Galilee Coal and Rail Project	Waratah Coal	40 ^a	Application
Kevin’s Corner Project	GVK Hancock	30 ^a	Application
South Galilee Coal Project	ACMI Group	17 ^a	Application

^aQueensland Gov. (2021a). *Completed projects*. URL: <https://www.statedevelopment.qld.gov.au/coordinator-general/assessments-and-approvals/coordinated-projects/completed-projects> (visited on 01/25/2022)

^bWaratah Coal (2021). *North Alpha Project*. URL: <https://www.waratahcoal.com/alpha-north-coal-project/> (visited on 01/25/2022)

²¹For official overview information, see the Queensland government website at <https://www.statedevelopment.qld.gov.au/coordinator-general/state-development-areas/current/galilee-basin-state-development-area> (visited on 08/24/2021).

In 2010, Adani’s application process for the Carmichael mine began and since then the project has gone through numerous judicial reviews, government decision-making as well as project changes. Indeed, the economic and environmental viability of the project has been questioned ever since 2010 by various stakeholders. Most importantly, this skepticism towards the Carmichael project led to a stop on external funding in 2018. As a consequence of the banks’ boycott of the Carmichael project, Adani has had to self-fund and downsize the project in 2018 from A\$16.5 billion to A\$2 billion (Hepburn 2021).

The shaky financial situation could not be relieved by the generous subsidies that the Carmichael project and the Adani parent company receive. The Carmichael mine benefits from subsidies from the Australian and Queensland governments that exceed A\$4.4 billion in total over the 30-year project life time (Buckley 2019b). In India, Adani Power Ltd. is also recipient of a number of subsidies including decade-long, government capital finance subsidies, dedicated special economic zone tax concessions and a special treatment on coal price pass-through (Buckley 2019b).

The Adani group’s rapid global expansion over the last decade has raised concerns due to its massive debt totaling in over \$30 billion in November 2020²². Effective 2019, Adani Mining had \$1.8 billion in debt as well as negative shareholder funds of A\$507 million in Australia. In addition, Adani’s Abbot Point Terminal had net liabilities of A\$1.8 billion secured by just A\$207 million book value of equity as well as a pre-tax loss of A\$25 million in 2018/19 (Buckley 2019a). The debt-funded purchase of the port led to around \$1 billion of debt coming due between 2020 and 2022.²³ As Adani failed to secure external funding to repay debt due in 2020 the company was forced to repay A\$270 million using funds from an Adani parent company. Consequently, the port’s credit rating was lowered several times in the last years.²⁴

The Carmichael mine will be the first mine in the Galilee Basin which will show whether mining in the Basin can be economically viable or not. We assume that the economic success of Carmichael is a prerequisite for the other mining projects to continue their application process and to start any mining operations. For this reason the Galilee Basin producer node is currently calibrated to represent Adani’s Carmichael mine. In 2019, the Queensland Resource Council (QRC) stated that the projects other than Adani’s Carmichael mine will have a ”much easier run” when the rail line is established and the environmental approvals have been cleared for Carmichael. Ian Macfarlane, the chief executive of the QRC, called the Carmichael Mine ”the

²²Stephanie Findlay and Hudson Lockett (2020). *‘Modi’s Rockefeller’: Gautam Adani and the concentration of power in India*. URL: <https://www.ft.com/content/474706d6-1243-4f1e-b365-891d4c5d528b> (visited on 06/15/2021)

²³Market Forces (2021). *Adani’s coal port failing to refinance debt, again*. URL: <https://www.marketforces.org.au/adanis-coal-port-failing-to-refinance-debt-again/> (visited on 06/21/2021)

²⁴Fitch Ratings (2019). *Fitch Affirms Adani Abbot Point Terminal at ‘BBB-’; Outlook Stable*. URL: <https://www.fitchratings.com/research/infrastructure-project-finance/fitch-affirms-adani-abbot-point-terminal-at-bbb-outlook-stable-05-11-2019> (visited on 06/21/2021); Fitch Ratings (2020). *Fitch Downgrades Adani Abbot Point Terminal to ‘BB+’; Ratings on RWN*. URL: <https://www.fitchratings.com/research/infrastructure-project-finance/fitch-downgrades-adani-abbot-point-terminal-to-bb-ratings-on-rwn-31-03-2020> (visited on 06/21/2021); S&P Global Ratings (2021). *Research Update: North Queensland Export Terminal Rating Lowered To ‘BB-’ On Refinancing Risks; Outlook Negative*. URL: <https://www.spglobal.com/ratings/en/research/articles/210329-research-update-north-queensland-export-terminal-rating-lowered-to-bb-on-refinancing-risks-outlook-negati-11897266> (visited on 06/21/2021)

ice-breaker that will lay down those baselines and will provide the infrastructure”.²⁵ Until 2021, only Adani has obtained all the state and federal approvals required for a mine in the Galilee Basin. It was granted its final environmental approval following the acceptance of the groundwater management plan in June 2019.²⁶ It started the construction of the mine in June 2019 and of the rail line in June 2020. In the following, we explain how the COALMOD-World parameters defining the Galilee Basin producer node were obtained.

Mining

The Carmichael mine project involves up to six open-cut pits, five underground mines, and mine processing facilities (Cassotta, Cueva, and Raftopoulos 2021)²⁷. The size of the Carmichael project was downsized several times and most drastically in 2018 after the company had failed to attract external funding. The project’s investment volume was reduced from A\$16.5 billion to A\$2 billion. These savings were mostly made possible by reducing the mine’s initial production capacity from 60 Mtpa to 10 Mtpa with plans to ramp up production to 27.5 Mtpa later.

The first two basic parameters characterizing the mine are the reserves as well as the coal’s average energy content. Over its operational lifetime of 60 years Carmichael is expected to produce up to 2300 Mtpa of steam coal with an average energy content of 4950 kcal (NAR) (Reddy and Rosencranz 2018)²⁸.

In order to analyse the economic viability of the construction and operation of Carmichael the initial production capacity as well as the initial transport capacity are set to 0 Mtpa. This means that investment into the necessary infrastructure are required before starting any mining operations. The investment costs are critical for the decision to invest in production capacity as well as in transportation capacity. Both parameters have the unit [million US\$/Mtpa] and assume a linear relationship between the production capacity built and the corresponding investment costs (i.e., unit costs).

The lower bound of the investment costs for new production capacity is based on estimates made by Buckley and Nicholas (2017) (Table 5). By subtracting the costs of the lease of the Abbot Point T1 terminal from the total investments made before 2018 we obtained the investments into mining capacity which were made before 2018. For later investments into mining capacity we used an estimate of the investments still required to reach a production level of 25 Mtpa (Buckley and Nicholas 2017). In the last step, we divided the total investments into mining capacity by the corresponding production capacity of 25 Mtpa to obtain unit cost estimates.

²⁵Jemima Burt (2021). *Adani could be ‘ice-breaker’ for six more proposed Galilee Basin mines, resources body says*. URL: <https://www.abc.net.au/news/2019-06-12/adani-approval-could-be-galilee-basin-ice-breaker/11194510> (visited on 06/21/2021)

²⁶ABC News (2021). *Adani gets final environmental approval for Carmichael mine*. URL: <https://www.abc.net.au/news/2019-06-13/adani-carmichael-coal-mine-approved-water-management-galilee/11203208> (visited on 06/21/2021)

²⁷Queensland Gov. (2021b). *Carmichael Coal Mine and Rail Project - Project overview*. URL: <https://www.statedevelopment.qld.gov.au/coordinator-general/assessments-and-approvals/coordinated-projects/completed-projects/carmichael-coal-mine-and-rail-project> (visited on 06/21/2021)

²⁸Australia Institute (2021). *The Coal Wars - Fact Check*. URL: https://australiainstitute.org.au/wp-content/uploads/2020/12/P303-Coal-hard-facts_0.pdf (visited on 06/21/2021)

Table 5: Calculations of lower bound of investment costs for new production capacity

	million A\$	million US\$
Investments before 2018		
Total investments	3500	2700
- Purchase of Abbot Point Terminal T1	2130	1650
= Investments into mining capacity	1370	1060
Investments after 2018		
Mining investments still required for 25 Mtpa	2050	1580
Total investments into mining capacity	3420	2640
CPinv		[million US\$/Mtpa]
Total investments into mining capacity / 25 Mtpa		106

Table 6: Calculations of upper bound of investment costs for new production capacity

	[million A\$]	[million US\$]
Investment		
Investment into mine and rail line	16500	12740,56
- Investment into rail line	2300	1775,96
= Investment into mine	14200	10964,60
CPinv		
Investment into mine / 60 Mtpa		182,74

The upper bound of the investment costs for new production capacity was calculated using Adani's original cost estimate for its project including the originally proposed 388 km long rail line (Table 6). Before downsizing the project, Adani had planned to build a 60 Mtpa mine and a 388 km long rail line for a total of 16.5 billion A\$, of which the rail line was estimated to cost 2.3 billion A\$.²⁹ Subtracting the latter from the cost of the whole project results in the cost of the 60 Mtpa mine. To determine our unit production investment cost parameter, the total cost of the mine was divided by the planned production capacity of 60 Mtpa.

Once investments into infrastructure have been made, operational costs accrue. The mine's operational costs are represented by a linear marginal cost function which is defined by a marginal cost intercept and a slope (Table 1). The operational costs are higher if the production level is high. In addition, the operational costs increase over time. The reason for this increase is that coal which is accessed easier is usually cheaper to mine and exploited first. We determine the intercept and slope by positioning a +/- 2 [US\$/t] interval around the average operational cost estimates provided by Tim Buckley and John Quiggin. The value by Buckley (2015) was used to calculate the lower bound of the marginal cost intercept. Buckley (2015) assumes a 30% cost advantage relative to 14 comparable steam coal mines in Queensland and New South Wales due to scale effects and the continuing productivity improvements evident across the mining

²⁹Lisa Cox (2018). *Adani ditches plan to build rail line for Carmichael coalmine*. URL: <https://www.theguardian.com/business/2018/sep/13/adani-ditches-plan-to-build-rail-line-for-carmichael-coalmine> (visited on 07/26/2021)

Table 7: Characteristics of Carmichael’s rail line to Abbot Point

Parameter	Lower Bound	Upper Bound	Remark
Initial transport capacity [Mtpa]		0	Forces the model to make the investment decision
Investment cost for transport capacity expansion [million US\$/Mtpa]	31.34 *	40.34 *	min. value: rail line cost = \$A1bn max. value: rail line cost = \$A1.5bn
Transportation cost [million US\$/Mtpa]	7.87	11.36	Min. value if rail line is not owned by an entity other than Adani Max. value if rail line is owned by an entity other than Adani Reality: Rail line is partly owned by Aurizon 189 km are owned by Adani

*inflation-adjusted

sector. Additionally, he included the costs for a coal handling and preparation plant (CHPP) as well as overhead labour costs. For both he also granted a 30% cost advantage due to the higher proportion of open-cut bypass coal and to the size of the project. The upper bound of the marginal cost intercept is based on the mining costs provided by Adani’s lawyers in January 2015 as reported in Quiggin (2017). Due to the equal length of the +/- 2 [US\$/t] intervals around the cost estimates the slope of the marginal cost curve is equal as well.

Railway transportation

Originally, Adani had planned to build a 388 km long narrow-gauge rail line from the Carmichael mine directly to the Abbot Point Port. Due to the funding problems, not only the mine but also the length of the railway project was shortened in 2018. The shorter, 189 km rail line connects to the existing Goonyella railway network by Aurizon.³⁰ The investment cost for transportation capacity as well as the transportation costs used in our model are stated in Table 7. The interval used for the transportation cost was estimated by Buckley (2015).

The new rail line is expected to cost between 1 billion A\$ and 1.5 billion A\$ and to carry up to 40 Mtpa of coal (IEA 2020b).³¹ In 2020, Adani launched it’s own rail company — Bowen Rail Company — to haul coal from the mine to the Abbot Point port. The cost of the Bowen Rail Company’s locomotives and coal wagons alone is estimated to cost additional 500 million A\$ for the mine’s second production stage (27 Mtpa) upfront.³² We use the costs of the rail

³⁰Adani’s new mini version of its mega mine still faces some big hurdles (2021). URL: <https://theconversation.com/adanis-new-mini-version-of-its-mega-mine-still-faces-some-big-hurdles-108038> (visited on 06/15/2021)

³¹Mark Carter (2018). *Adani rethinks Queensland coal line project*. URL: <https://www.railjournal.com/freight/adani-rethinks-queensland-coal-line-project/> (visited on 06/21/2021); Cole Latimer (2018). *Adani coal mine hinges on a rail line in doubt*. URL: <https://www.smh.com.au/business/the-economy/adani-coal-mine-hinges-on-a-rail-line-in-doubt-20181130-p50jgi.html> (visited on 06/21/2021)

³²Josh Robertson (2021). *Adani launches own rail company to haul coal from Carmichael mine*. URL: <https://www.abc.net.au/news/2020-09-10/adani-coal-mine-abbot-point-terminal-rail-line-protests/12644432> (visited on 06/21/2021)

Table 8: Calculations of lower bound of investment costs for new transportation capacity

	[million A\$]	[million US\$]
Cost of rail line	1000	772,16
Inflation adjustment	932,71	720,20
Cost of rail line / 40 Mtpa		18,0
Cost of coal wagons and locomotives for 27 Mtpa	500	386,08
Inflation adjustment	466,36	360,10
Cost of coal wagons and locomotives / 27 Mtpa		13,34
CTinv_e		[million US\$/Mtpa]
+ Cost of rail line / 40 Mtpa		18,0
+ Cost of coal wagons and locomotives / 27 Mtpa		13,34
= Investment cost for new transportation capacity		31,34

Table 9: Calculations of upper bound of investment costs for new transportation capacity

	[million A\$]	[million US\$]
Cost of rail line	1500	1158,23
Inflation adjustment	1399,07	1080,30
Cost of rail line / 40 Mtpa		27,01
Cost of coal wagons and locomotives for 27 Mtpa	500	386,08
Inflation adjustment	466,36	360,10
Cost of coal wagons and locomotives / 27 Mtpa		13,34
CTinv_e		[million US\$/Mtpa]
+ Cost of rail line / 40 Mtpa		27,01
+ Cost of coal wagons and locomotives / 27 Mtpa		13,34
= Investment cost for new transportation capacity		40,34

line as well as the costs of the operational rail equipment to determine the investment cost for new transport capacity (Table 8, Table 9).

Export terminal

We use the Abbot Point Terminal characteristics for the new export node of the Galilee Basin in the COALMOD-World model. Adani’s plans for the terminal changed several times since the project development started in 2010. In 2011, Adani Ports and Special Economic Zone Ltd. (formerly known as Mundra Port Pty Ltd.), a subsidiary of the Adani group, signed a 99-year lease on the 50 Mtpa Abbot Point Terminal 1 for US\$ 1.98 billion³³. However, Adani could not use the terminal’s entire capacity immediately. External clients such as Glencore and BHP Mitsui also rent parts of the port’s capacity with take-or-pay contracts covering approximately 34 Mtpa in 2021. Buckley, Nicholas, and Walters (2017) estimate that externally contracted capacity steadily declines to 0 Mtpa in 2030. Since the export capacity parameter

³³Chris Nicholson (2011). *Adani of India to Buy Australian Port for \$2 Billion*. URL: <https://dealbook.nytimes.com/2011/05/03/indias-adani-to-buy-australian-port-for-2-billion/> (visited on 08/10/2021)

Table 10: Characteristics of the Abbot Point export terminal

Parameter	Lower Bound	Upper Bound	Remark
Export capacity [Mtpa]	25	50	
Investment cost for export capacity expansion [million US\$/Mtpa]	8	82	min. value: E_AUS.QLD and E_AUS_NSW max. value: estimated cost for building T0 terminal (50 Mtpa)
Port fee [US\$/t]	4.6	5	

in the COALMOD-World model is fixed and not time-dependent, we use a broad interval of 25 to 50 Mtpa for this parameter to account for the external capacity users (Table 10). Bravus Mining (originally Adani Mining) has signed a contract for 9.3 Mtpa beginning 2023 to service its Carmichael Mine.³⁴

Despite the port’s low annual utilization rate of 49-64% in 2016-21,³⁵ plans to expand the terminal’s current capacity of 50 Mtpa have been made in the past.³⁶ In 2015, the government of Queensland approved plans to expand the port’s capacity to up to 120 Mtpa.³⁷ As of today, none of the expansion plans are close to being realized. In July 2018, Adani applied to expand Abbot Point’s export capacity by 10 Mtpa without building a new export terminal. This expansion is estimated to cost 100 million A\$.³⁸ We determine the lower bound of the investment cost for export capacity by dividing the cost of this expansion by the added capacity of 10 Mtpa (Table 10).

Adani’s long term plans to build a new 50 Mtpa export terminal (“T0”) for estimated 5.3 billion A\$ dates back to 2010 when the capacity of the existing terminal T1 had been entirely contracted out to other mining companies leaving no free capacity for Carmichael (Buckley and Nicholas 2017). The construction plans of T0 gives us the values of the upper bound of the investment cost for new export capacity (Table 10). The use of the T1 terminal requires a port fee (Buckley 2015; Quiggin 2017) which gives us the operational export terminal costs in COALMOD-World.

³⁴Fitch Ratings (2019). *Fitch Affirms Adani Abbot Point Terminal at 'BBB-'; Outlook Stable*. URL: <https://www.fitchratings.com/research/infrastructure-project-finance/fitch-affirms-adani-abbot-point-terminal-at-bbb-outlook-stable-05-11-2019> (visited on 06/21/2021)

³⁵North Queensland Bulk Ports Corporation (NQBP) (2021). *North Queensland Bulk Ports Corporation - Throughput*. URL: <https://nqbp.com.au/trade/throughputs> (visited on 06/21/2021)

³⁶Global Energy Monitor Wiki (2021). *Abbot Point Coal Terminal*. URL: https://www.gem.wiki/Abbot_Point_Coal_Terminal#cite_note-13 (visited on 06/21/2021)

³⁷Allyson Horn and Elaine Ford (2021). *Abbot Point: Federal Government approves huge coal port expansion near Great Barrier Reef*. URL: <https://www.abc.net.au/news/2015-12-22/massive-abbot-point-coal-port-expansion-gets-federal-approval/7047380> (visited on 06/21/2021)

³⁸Ben Smee (2018). *Adani lodges slimmed-down plan to expand Abbot Point coal terminal*. URL: <https://www.theguardian.com/business/2018/aug/01/adani-lodges-slimmed-down-plan-to-expand-abbot-point-coal-terminal> (visited on 08/10/2021)

B Coal demand and climate policies - country details

Australia

Although the majority of the coal produced in Australia is exported, coal also plays a significant role in domestic power generation. 94% of the domestic coal consumption is used for electricity production, only 6% are used as coke or otherwise in the industry (Jotzo, Mazouz, and Wiseman 2018, p. 6). In 2018, steam coal had a 45% share in the national electricity generation (brown coal: 13%), while renewable energies accounted for only 20% of total electricity generation. However, there is a clear downward trend for coal which will further intensify in the next years.

In 2000, coal still accounted for 83% of the electricity mix³⁹. Since then, coal consumption in Australia has been declining and renewable energies developing very fast. Their share doubled within the last 20 years, pushed by increasingly ambitious support policies and decreasing costs. The share of renewable energies is expected to reach 40% by 2030 (Atholia, Flannigan, and Lai 2020, p. 43). Australia's latest greenhouse gas reduction target was updated in the fall of 2021 according to which Australia aims to achieve climate neutrality by 2050 (Australian Government Department of Industry, Science, Energy and Resources 2021a, p. 3).

At the same time, many coal-fired power plants are reaching the end of their lifetime in the 2020s and there is a big chance to replace them with climate-friendly technologies. Between 2012 and 2017, ten coal fired power plants with a total capacity of 5.3 GW were retired in the National Electricity Market (NEM) in Australia. Their average age at the time of retirement was 40 years. The remaining 18 coal fired power plants (15 steam coal, 3 brown coal) had already an average age of 33 years in 2018 (Jotzo, Mazouz, and Wiseman 2018, p. 11). Consequently, with an expected economic lifetime of 40 to 50 years many coal fired power plants will probably retire in the near future. Almost all operating coal fired power plants with a capacity around 25 GW will retire until 2050, half of them will reach their end-of-life age already between 2030 and 2040. Even if considering a possible lifespan extension, the upcoming decline of Australian coal power capacity is still significant. It is estimated that only 7 GW are able to be life-extended due to company commitments and high investment costs.⁴⁰

When costs for renewable energies continue to fall and, therefore, electricity from renewable energy will be cheaper than from coal, it appears economically reasonable to retire coal plants even before they reach their technical end-of-life age (Jotzo, Mazouz, and Wiseman 2018, p. 12). In late 2021, the Australian government announced that it would close coal power plants with a capacity of 5 GW earlier than originally announced. Accordingly, the total coal capacity in Australia would be at most 14 GW by 2030 which is a reduction of 44% compared to 2019 (Australian Government Department of Industry, Science, Energy and Resources 2021b, p. 19). The remaining coal-fired power plants are ultimately expected to operate at only 80% of capacity compared to 2019 levels (Bowyer 2021, p. 5).

As there will be a gap between the declining coal fire plant capacity and an expected growing

³⁹Department of the Environment and Energy (2020). *Australian Energy Update 2020*. URL: <https://www.energy.gov.au/publications/australian-energy-update-2020> (visited on 09/10/2021), Table O.

⁴⁰Bloomberg New Energy Finance (2019). *The inevitable decline of Australia's coal generation*. URL: <https://www.poweringpastcoal.org/insights/energy-security/the-inevitable-decline-of-australias-coal-generation> (visited on 04/20/2021).

electricity consumption, this gap has to be filled. Filling this gap by building new coal fired power stations seems very unlikely, despite possible support from the conservative government. Declining levelized cost of energy (LCOE) of renewable energies, less baseload demand, very long construction time of coal fired power plants, risks of future carbon policies and reputation loss has made it unattractive to invest in new coal fired power plants (Jotzo, Mazouz, and Wiseman 2018, p. 11). Also the possibility of replacing existing coal fired power plants with high efficient and less emission (HELE) coal power plants or improving the technical efficiency of the existing plants is very unlikely. Only little improvements in efficiency are expected from HELE coal power plants, so this is considered to not be economically viable by the industry (Webb, Silva, and Wilson 2020, p. 373) (PwC 2019, p. 25).

China

With the industrialization and the accompanying increase in energy demand, China's demand for coal has increased greatly over time and has become a driving factor in the Chinese economy. In 2018, coal power generation was 1367 times higher than in 1949 (H. Zhang, X. Zhang, and Yuan 2020, p. 6). This huge increase led to the rapid development of China's power industry, but also made China the largest emitter of CO_2 . In 2020, the Chinese coal-fired power plant fleet with its capacity of more than 1,000 GW (Global Energy Monitor 2021) was responsible for 15% of the global greenhouse gas emissions (IEA 2021a, pp. 18, 21–22). However, in the long term China wants to reduce the greenhouse gas emissions and set the goal to achieve net-zero by 2060 (Chinese Government 2021, p. 2). Whether China will be able to achieve this goal and decarbonize its very coal-based energy sector, though, is questionable. As China has a very young coal-fired power plant fleet, but with an average age of 15 years, it will be a major challenge for China to phase out coal combustion in the near future (Cui et al. 2021, p. 2).

Even though the share of coal in the power sector has dropped from 90% in 2009 (IEA 2021a, p. 23) to about 65% in 2019 (BP 2021, p. 65), China is by far the world's largest coal consumer. At the same time, China is also the largest coal producer, however, the country does not produce enough coal to completely meet its domestic demand and is dependent on imports from other countries, including Australia (IEA 2021a, p. 23). Although there does not exist a concrete long-term phase out plan for coal, China's president recently announced that the coal consumption should be limited until 2025 and decline thereafter. As a result, China's greenhouse gas emissions should peak before 2030 to achieve the goal of climate neutrality by 2060⁴¹.

India

Since 1973 coal fired power generation in India has grown steadily and had a share of 74% in the electricity generation mix in 2017 (IEA 2020d, pp. 229–230). With an annual steam coal consumption of almost 800 Mt, India is the second largest coal consumer in the world after China (IEA 2019, pp. VI.17–VI19). India has large coal reserves, most of them located in the

⁴¹Reuters (2021). *President Xi says China will start cutting coal consumption from 2026*. URL: <https://www.reuters.com/world/china/chinas-xi-says-china-will-phase-down-coal-consumption-over-2026-2030-2021-04-22/> (visited on 11/26/2021).

eastern region of the country (IEA 2021d, p. 34; IEA 2020d, p. 233). Although domestic Indian coal has a poor quality, most of the Indian coal fired power plants with a total capacity of 230 GW (Global Energy Monitor 2021) use domestic coal. Growing coal demand has also led to a strong increase in steam coal imports, especially from Indonesia and South Africa. Power plants with a capacity of 18 GW were especially built for the combustion of imported coal (IEA 2021d, p. 233). The Adani project in Australia is a project that supports the trend to imports.

Despite the high reliance on fossil fuels, the Indian government set a goal to reduce the emission intensity of GDP by 33-35% until 2030 from 2005 levels. At the same time the share of non-fossil fuels should be increased to 40% of the electricity mix (Indian Government 2016, p. 29). At the COP26 in fall 2021 the Indian Premier Minister announced that India wants to reach climate neutrality by 2070⁴². In the National Electricity Plan from 2018, the government defines a pathway for electricity generation until 2027. As electricity demand is expected to increase considerably, the coal fired power plant capacity should be 238 GW in 2027 compared to 192 GW in 2017 (CEA 2018, pp. 1.3, 5.16–5.17). Consequently, in 2027 around 40% more coal would be needed for electricity generation than in 2017 (CEA 2018, pp. 9.7–9.8). However, the government has also committed to an increase of the capacity of renewable energies. Whereas the capacity of renewable energies (withouth hydro power) was 57 GW in 2017, it should increase to 275 GW in 2027 (CEA 2018, pp. 1.3, 5.16–5.17).

Japan

As the fifth largest consumer of steam coal in the world (IEA 2019, p. 47), Japan plays a significant role in the world's coal market. Coal accounts for 27% of Japan's total primary energy supply, 60% of the coal used in Japan is used for power generation. With a coal power plant fleet with a total capacity of 48 GW (2020), coal accounted for 32% of electricity generation in 2019 and is the second most important source of electricity generation after natural gas. After the earthquake and the resulting nuclear accident in Fukushima in 2011, all nuclear power plants in Japan were closed which led to an increase of coal consumption by 14% between 2011 and 2013. Due to the reopening of some nuclear power plants, the slow rise of renewable energies and reduced demand in the steel industry the share of coal in total energy consumption has slowly declined since 2014 (IEA 2021e, pp. 195–196).

Although Japan announced in 2021 to be carbon neutral by 2050 (Japanese Government 2021, p. 1), the country has no long-term plan for phasing out coal combustion. Arguing that coal represents a low-cost and important base load power supply, Japan aims to hold on to coal combustion with a focus on high efficiency, low emissions coal fired power plants, potentially including carbon capture, utilization and storage facilities (CCUS) in the future (METI 2018, p. 24). As a consequence, the government plans to close about 100 old and inefficient coal fired power plants by 2030.⁴³ In the Long-term Energy Supply and Demand Outlook, which was

⁴²BBC (2021). *COP26: India PM Narendra Modi pledges net zero by 2070*. URL: <https://www.bbc.com/news/world-asia-india-59125143> (visited on 11/25/2021).

⁴³Reuters (2020). *Japan to shut or mothball 100 ageing coal-fired power plants -Yomiuri*. URL: <https://www.reuters.com/article/uk-japan-powerstation-coal-idUKKBN24306U?edition-redirect=uk> (visited on 06/01/2021).

published in 2015, the Japanese government aimed at a coal share in the power sector of 26% by 2030 (METI 2015, p. 8). In 2021, however, this target was revised to 19% with a parallel expected decline in energy demand due to energy efficiency improvements in buildings and factories. Therefore, the total coal power output should decline by 46% between 2019 and 2030. In addition to coal, gas-fired power generation is to be reduced, while the share of renewable energies should be significantly increased by 2030 (METI 2021, p. 12).⁴⁴ Although there are short-term coal phase down plans, there are no coal phase-out plans by the government that go beyond the plans by 2030.

South Korea

Also in South Korea coal still plays a very important role in the energy supply. Since 2000 coal demand in South Korea has almost doubled and has now a share of 29% in the total primary energy supply and 44% in electricity production. The domestic coal production is negligible which makes South Korea one of the world's largest importers of coal. 99% of the coal used in South Korea is imported, more than one third of it comes from Australia (IEA 2020e, pp. 173–175).

Like Japan, the government of South Korea announced that it aims to be carbon neutral by 2050. Therefore, South Korea plans to close coal fired power plants or convert them into LNG fired power plants. In addition, there will also be a focus on carbon capture, storage and utilization (CCUS) to further reduce emissions (The Government of the Republic of Korea 2020, pp. 7–8). In its *9th Basic Plan for Long-Term Electricity Supply and Demand*, which was published 2020, the Ministry of Trade, Industry and Energy gives an outlook on the electricity market: By 2030 the coal fired power plant capacity should fall to 32.6 GW from 36 GW in 2020. Until 2034 this capacity should decline further to 29 GW. As a result, the coal fired power output in 2030 should be 23% lower than in 2019.⁴⁵ In fall 2021, South Korea announced a steeper decline in coal demand so as to achieve a complete coal phase out by 2050 (Argus Media 2021c).

Taiwan

Unlike Japan and South Korea, Taiwan does not yet have an official net-zero carbon target. The current official target is only a 50% reduction in greenhouse gas emissions by 2050 compared to 2005⁴⁶. Recently, however, the government finally announced that it will also pursue a carbon-neutral plan by 2050, though it did not yet specify any concrete steps⁴⁷. But to achieve this goal Taiwan must move away from its strong fossil dependence.

⁴⁴Argus Media (2021a). *Japan cuts 2030 coal/gas power share targets*. URL: <https://www.argusmedia.com/en/news/2236379-japan-cuts-2030-coalgas-power-share-targets> (visited on 11/26/2021).

⁴⁵Argus Media (2021b). *Seoul reaffirms its commitment to reduce coal reliance*. URL: <https://www.argusmedia.com/en/news/2174529-seoul-reaffirms-its-commitment-to-reduce-coal-reliance> (visited on 07/28/2021); Wood Mackenzie (2021). *South Korea's 9th Basic Plan for electricity – a step closer to carbon neutrality?* (Visited on 07/28/2021).

⁴⁶Laws and Regulation Database of The Republic of China (2015). *Greenhouse Gas Reduction and Management Act*. URL: <https://law.moj.gov.tw/ENG/LawClass/LawAll.aspx?pcode=00020098> (visited on 06/02/2021).

⁴⁷Taiwan News (Aug. 31, 2021). *Taiwan eyes net zero emissions by 2050*. Taiwan News. Section: Environment. URL: <https://www.taiwannews.com.tw/en/news/4279634> (visited on 11/25/2021).

In 2021, Taiwan operated 20 coal fired power plants with a total capacity of 19 GW (Global Energy Monitor 2021), coal accounted for 45% in the electricity mix in Taiwan in 2020⁴⁸. Following the new leitmotif to "promote green energy, increase natural gas, reduce coal-fired, achieve nuclear-free", no new coal-fired power plants will be built and existing power plants will be converted to gas after 2025.⁴⁹ The goal is to achieve a coal share in the electricity market of 41% in 2023 and 27% in 2025 (2019: 46%), which means a reduction in coal fired power output of 33% by 2025 (Bureau of Energy, MOEA 2018, p. 10). However, long-term coal phase-out plans have not yet been announced.

⁴⁸Bureau of Energy, MOEA (2020). *Energy Statistics in Q4 2020*. URL: https://www.moeaboe.gov.tw/ECW/English/news/News.aspx?kind=6&menu_id=958&news_id=19813 (visited on 06/03/2021), Figure 4.

⁴⁹Bureau of Energy, MOEA (2021). *Energy Transition Promotion Scheme. Promote Green Energy, Increase Nature Gas, Reduce Coal-fired, Achieve Nuclear-free*. URL: https://www.moea.gov.tw/MNS/english/Policy/Policy.aspx?menu_id=32904&policy_id=19 (visited on 06/03/2021).

C CMW coal demand scenarios - data

Table 11: Steam coal demand in the *High demand* in PJ

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Bangladesh	88	92	353	348	342	337	331	308	308	196
China	73,445	76,814	80,654	78,349	74,509	69,132	60,684	36,871	19,971	4,609
India	14,420	16,862	18,379	17,030	16,187	15,345	14,670	12,477	6,070	2,361
Indonesia	1,907	3,954	5,061	4,943	4,824	4,152	4,152	3,756	2,135	989
Japan	3,625	3,627	3,446	2,720	2,249	1,523	943	725	653	363
Malaysia	575	841	824	774	765	690	538	294	235	0
Pakistan	111	344	492	482	468	458	451	440	440	141
Philippines	381	648	745	732	700	499	492	454	376	104
South Korea	2,512	2,286	2,309	1,829	1,463	1,029	869	320	0	0
Taiwan	1,403	1,420	1,250	1,150	937	554	284	227	227	0
Thailand	450	353	346	342	198	116	116	102	14	0
Vietnam	75	1,209	1,548	1,499	1,451	1,402	1,330	1,221	701	339

Table 12: Steam coal demand in the *Moderate decline* scenario in PJ

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Bangladesh	88	92	310	260	247	247	156	0	0	0
China	73,445	76,814	70,668	59,146	36,871	19,971	4,609	0	0	0
India	14,420	16,862	13,995	11,634	9,949	4,721	1,855	0	0	0
Indonesia	1,907	3,954	3,756	3,321	3,005	1,700	791	0	0	0
Japan	3,625	3,627	1,705	689	580	508	290	0	0	0
Malaysia	575	841	631	429	235	193	0	0	0	0
Pakistan	111	344	420	354	354	354	114	0	0	0
Philippines	381	648	460	389	363	298	84	0	0	0
South Korea	2,512	2,286	1,623	1,006	732	663	251	0	0	0
Taiwan	1,403	1,420	1,420	540	213	185	185	0	0	0
Thailand	450	353	233	198	81	11	0	0	0	0
Vietnam	75	1,209	1,318	1,028	979	568	266	0	0	0

Table 13: Steam coal demand in the *1.5°* scenario in PJ

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Bangladesh	88	92	56	27	10	1	0	0	0	0
China	73,445	76,814	46,933	22,736	8,296	537	384	154	0	0
India	14,420	16,862	10,303	4,991	1,821	117	84	34	0	0
Indonesia	1,907	3,954	2,416	1,170	427	28	20	8	0	0
Japan	3,625	3,627	1,864	649	287	145	0	0	0	0
Malaysia	575	841	514	249	91	6	4	2	0	0
Pakistan	111	344	210	102	37	2	2	1	0	0
Philippines	381	648	396	192	70	5	3	1	0	0
South Korea	2,512	2,286	1,397	677	247	16	11	5	0	0
Taiwan	1,403	1,420	868	420	153	10	7	3	0	0
Thailand	450	353	216	104	38	2	2	1	0	0
Vietnam	75	1,209	739	358	131	8	6	2	0	0

D Sensitivity analysis and additional results

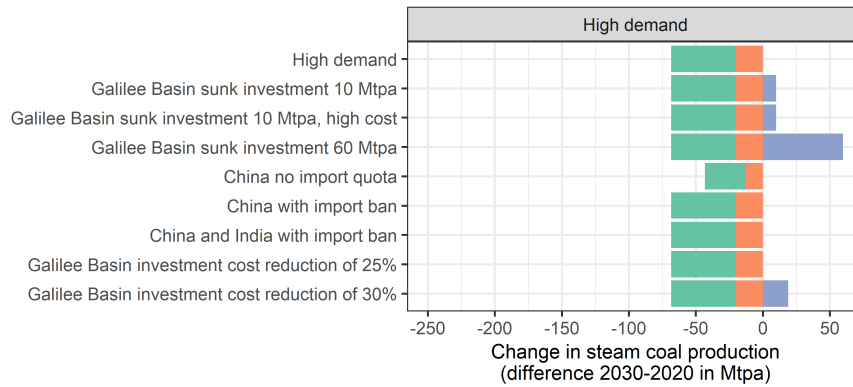
Figure 8 shows changes in Australian steam coal production between 2020 and 2030 for various sensitivity runs in all three scenarios.

Three different sensitivities are implemented to test the effect of Chinese and Indian import policies. 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.⁵⁰ In case these restrictions continued, we would expect a continuous rerouting of trade flows with limited influence on exporters' production volumes. It would be a somewhat different case if China (or India) were to ban all coal imports and enforce autarkic supplies from domestic production, which was discussed by Chinese (and Indian) politicians in recent times.⁵¹ A complete import ban in China and India ("China and India with import ban" in panels (a)-(c) in Figure 8) shows that Australian exports in the *High demand* scenario would be only slightly affected, though, because exports are rerouted to other Asian countries, while Indonesia's exports would be affected more heavily. As soon as demand is lower as in the *Moderate decline* scenario, Australian exports will be heavily affected because demand in other Asian countries will be much lower. Lastly, if China removed its import quota (currently limiting total steam coal imports to approximately 300 Mt per year), Australian production would be slightly higher than with the Chinese import quota in the *High demand* and *Moderate decline* scenarios.

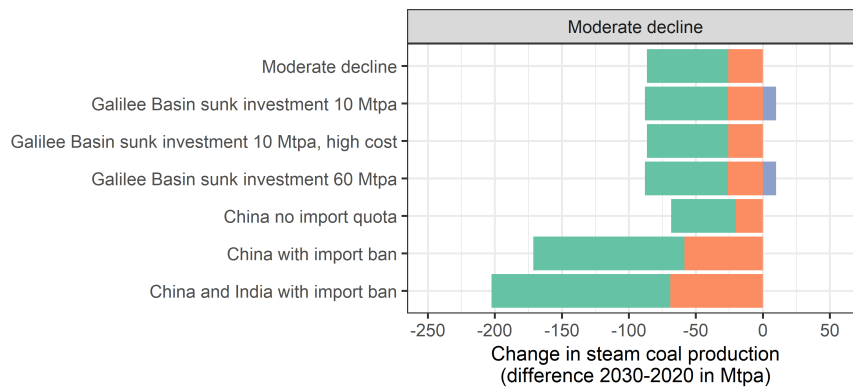
⁵⁰Cissy Zhou and Su-Lin Tan (2022). *China-Australia relations: as demand for coal surges, how long can Beijing keep banning Australian supply?* URL: <https://www.scmp.com/economy/china-economy/article/3147774/china-australia-relations-demand-coal-surges-how-long-can> (visited on 01/05/2022)

⁵¹Bloomberg News, March 14, 2022: China Seeks to Cut Reliance on Coal Imports With Mining Boom. <https://www.bloomberg.com/news/articles/2022-03-14/china-seeks-to-cut-coal-import-reliance-with-mining-boom> (visited on 03/29/2022); ET Energyworld.com, February 15, 2022: India to be self-dependent in coal production for thermal power generation by 2024: Secy. <https://energy.economictimes.indiatimes.com/news/coal/india-to-be-self-dependent-in-coal-production-for-thermal-power-generation-by-2024-secy/89594488> (visited on 03/29/2022)

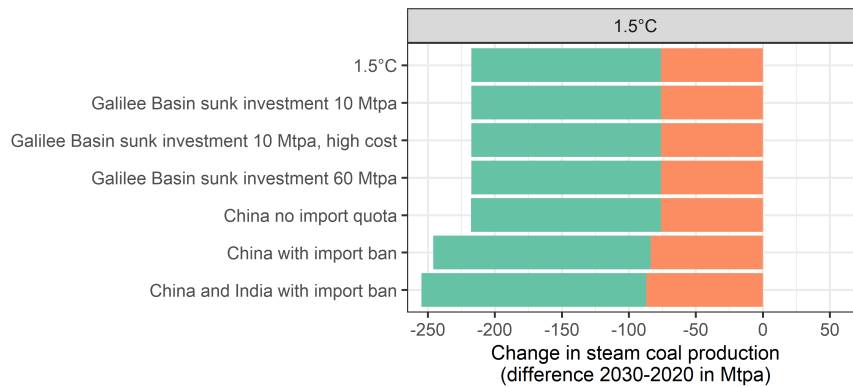
(a)



(b)



(c)



■ New South Wales ■ Queensland ■ Galilee Basin

Figure 8: Change in Australian steam coal production between 2020 and 2030 in all scenarios.

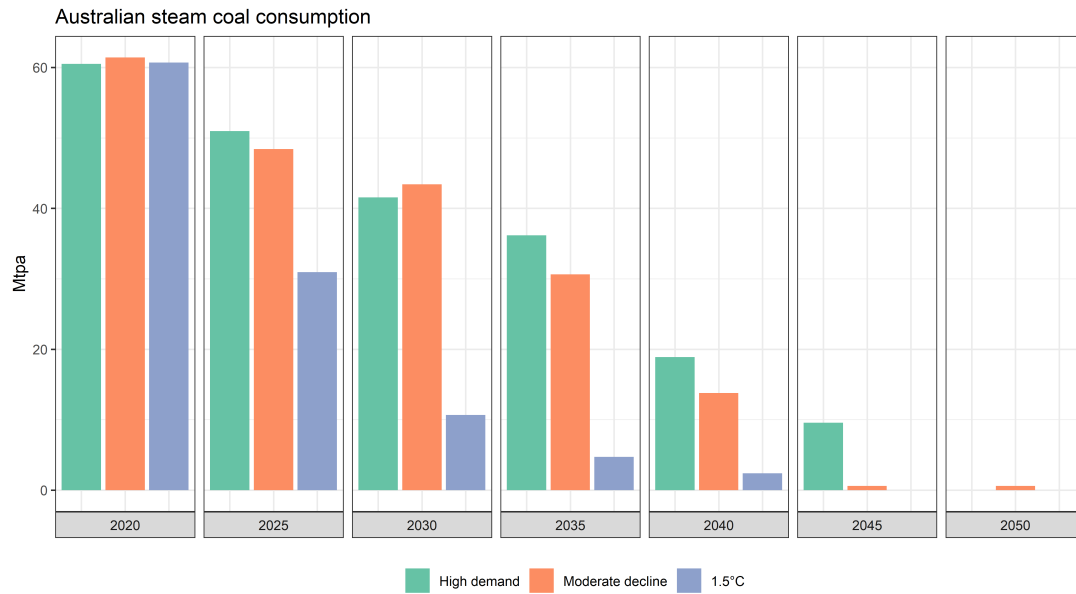


Figure 9: Australian steam coal consumption in all scenarios in Mt per year.

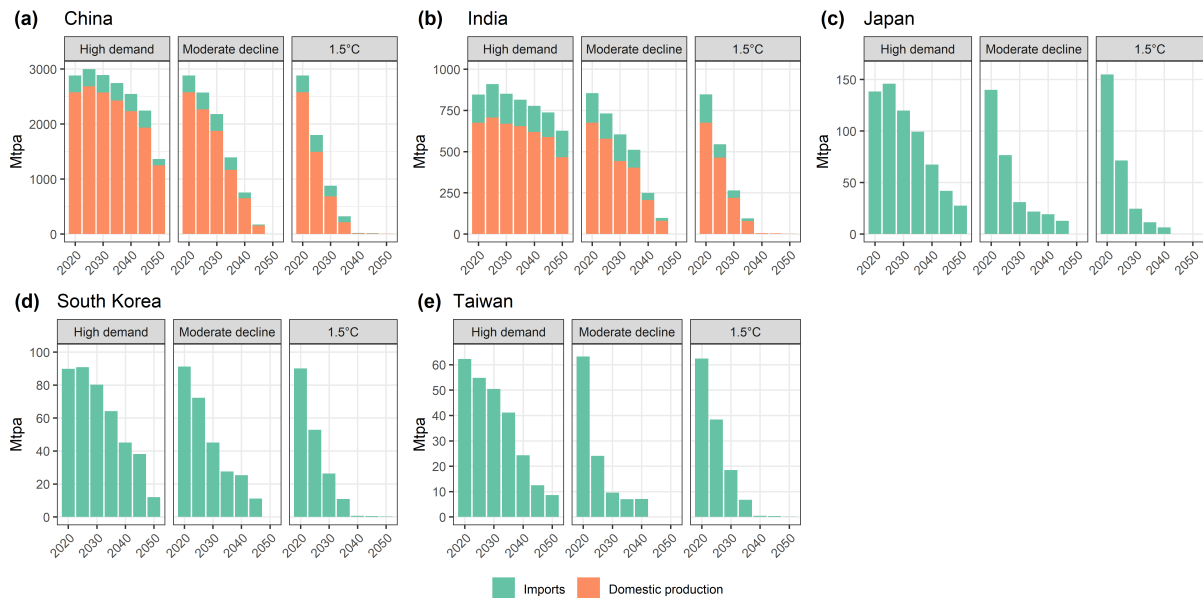


Figure 10: Steam coal domestic production and imports in China (a), India (b), Japan (c), South Korea (d) and Taiwan (e) in all scenarios.

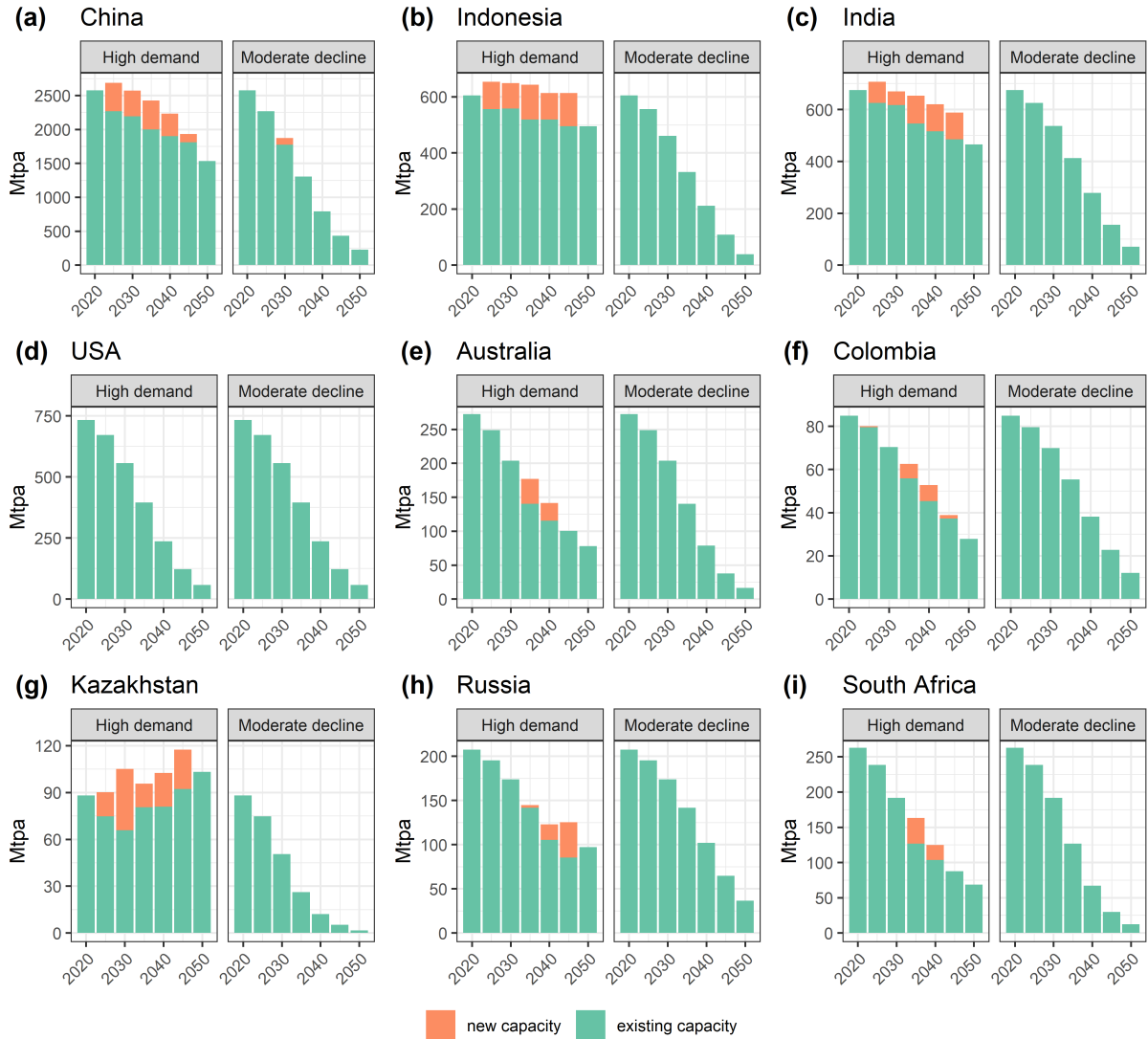


Figure 11: Available steam coal production capacity in major coal producing countries in all three scenarios in Mt per year (2020-2050). 'New capacity' denotes capacity addition (in year a) based on investment in previous model period (year $a - 1$). 'Existing capacity' denotes remaining capacity from previous model periods.