Australia's National Science Agency

Modelling the emissions impact of additional LNG in Asia

A report for Woodside Energy Pty Ltd

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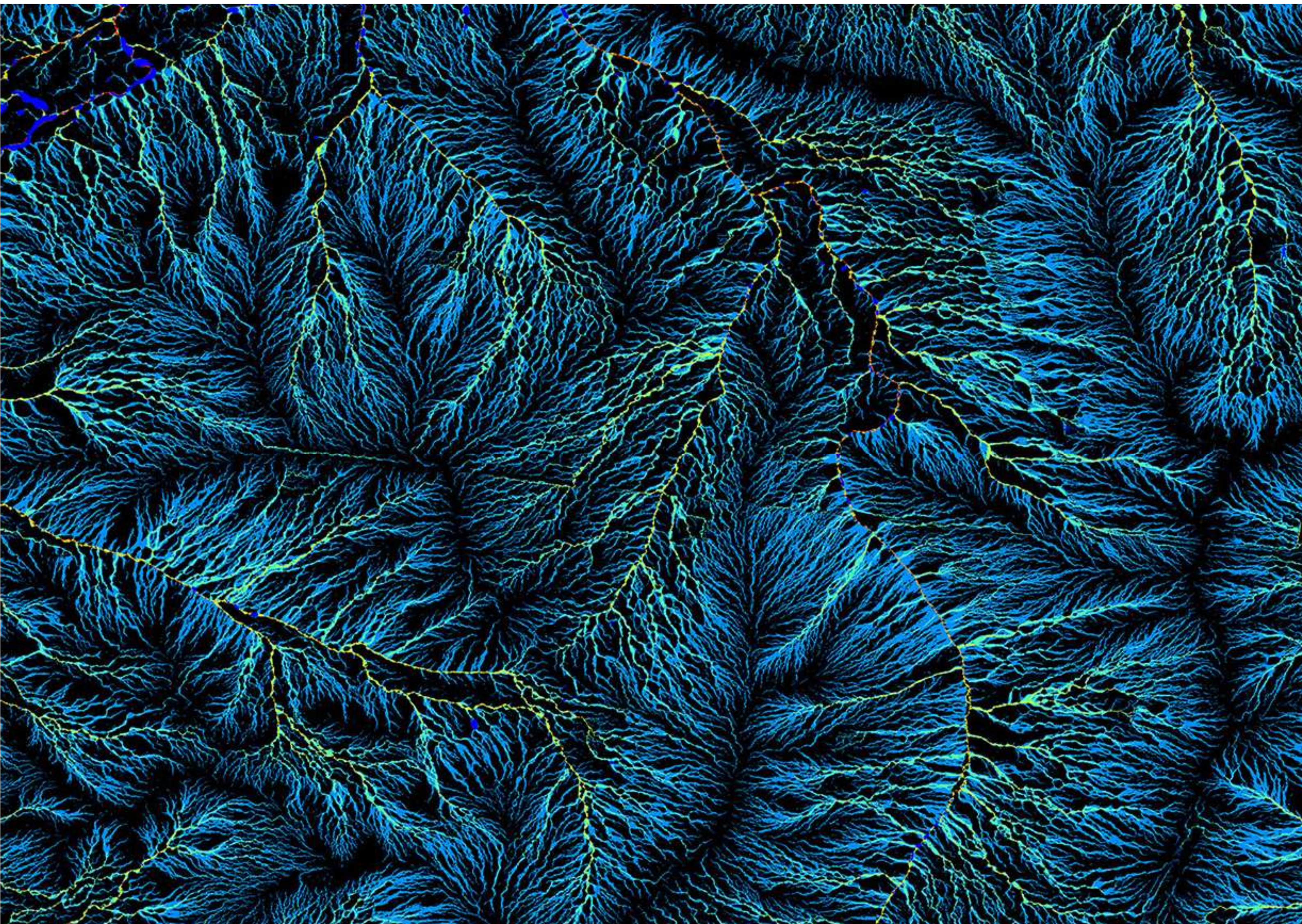

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Executive summary

The aim of this study is to understand the impact additional liquefied natural gas (LNG) may have on greenhouse gas (GHG) emissions in Asian regions and globally, through changes to technologies and fuels used to generate electricity. LNG has long been considered as the 'transition fuel' towards decarbonisation of electricity generation. Under this concept, the use of gas is increased to replace more emissions-intensive coal-fired generation while renewable or other very low emissions technologies increase their installed capacity and reduce their cost through learning-by-doing, eventually replacing the need for increased use of gas. CSIRO has used its Global and Local Learning Model – Electricity (GALLM-E) and two climate change scenarios to project future electricity generation mixes consistent with reducing emissions in the global electricity sector. Within the emission reduction scenarios, different gas supply scenarios have been explored: Baseline, 10% and then 20% increase in supply to all Asian markets; followed by a 10% and then 20% increase in supply to China only. China is a very large contributor to total Asian and global GHG emissions, has fast growing electricity demand and has good access to renewable energy resources. A high-level summary of the results and strategic implications is presented below.

Sustainable Development Scenario equivalent

In this scenario a high carbon price is applied uniformly to all regions from the year 2025 onwards in order the replicate the electricity sector emission reduction in the IEA's Sustainable Development Scenario (SDS). A carbon price has the effect of reducing high emission generation and l supporting low emissions electricity generation technology deployment. Countries may use other mechanisms for incentivising a similar outcome, however a carbon price is useful for our purposes because it is technology neutral.

Summary 1: Increase gas supply to all Asian markets

Table 1 Summary of impacts of increase in gas supply to all Asian markets under the SDS-equivalent scenario

	2020-2040		2040+	
	10% increase	**20% increase**	**10% increase**	**20% increase**
High renewable energy resource region	Does not divert region from Baseline renewable path	Enhances adoption of renewables through supporting role	No change	No change

Low renewable energy resource region	Delays their adoption of low emission technologies (higher emissions)	No change	Gas CCS partially substitutes for some high cost renewables	No change
Global	No net benefit	Substantial emissions benefit	No net benefit	No net benefit
Asia	No net benefit	Substantial emissions benefit	No net benefit	No net benefit

Strategic implications

- Low renewable energy resources regions (e.g. India, Japan, South Korea and South East Asia) should not be targeted for increased gas exports, or if targeted at all, only after they have exhausted renewable options
- Targeting high renewable energy resource regions (e.g. China) produces no harm and potentially has substantial benefits in supporting renewable deployment to 2040.

Summary 2: Increase gas supply to China only

China is a large market with high renewable energy resources. Increasing gas supply to this market provides a test for whether the second strategic implication above can be observed in the model.

Table 2 Summary of impacts of increase in gas supply to China only under the SDS-equivalent scenario

	2020-2040		2040 +	
	10% increase	**20% increase**	**10% increase**	**20% increase**
High renewable energy resource region	Enhances adoption of renewables through supporting role	Enhances adoption of renewables through supporting role	Enhances adoption of renewables through supporting role	No change
Low renewable energy resource region	No change	No change	Gas CCS partially substitutes for some high cost renewables	Gas CCS partially substitutes for some high cost renewables
Global	Substantial emissions benefit	Substantial emissions benefit	No net benefit	No net benefit

Asia	Substantial emissions benefit	Substantial emissions benefit	No net benefit	No net benefit

Strategic implications

- In low renewable energy resource regions, the technology mix is shifted to gas carbon capture and storage (CCS) long term if there is more abundant gas but otherwise unimpacted.
- Targeting high renewable energy resource regions potentially has substantial benefits in supporting renewable deployment to 2040.
- Targeting only high renewable energy resource countries means that a smaller amount of gas can reduce emissions whereas when a small amount of gas is targeted everywhere the impact of delaying action elsewhere means a small amount of gas has no emissions benefit.

Note on South East Asia (SEA)

SEA is a low renewable energy resource region. Unlike India, gas does reduce coal-fired electricity and increases renewable penetration in all SDS-equivalent scenarios, except in the 10% increase in gas supply to China case. However, because of the lower demand in this region compared to India, it has a lower impact on global GHG emissions.

4-degrees scenario

The 4-degrees (4DS) scenario has a low carbon price which only applies in some regions. Therefore, it is expected that high emissions technologies such as coal-fired generation will continue to meet electricity demand, especially from older plants where the capital cost is sunk. In this case, an increase in gas availability will most likely have a negative impact on renewable electricity generation deployment.

Summary 3: Increase gas supply to all Asian markets

Table 3 Summary of impacts of increase in gas supply to all Asian markets under the 4DS scenario

	2020-2040		2040+	
	10% increase	**20% increase**	**10% increase**	**20% increase**
High renewable energy resource region	No change	No change	No change	No change

Low renewable energy resource region	No change	No change	Delays their adoption of low emission technologies	Supports deployment of high cost renewables
Global	No net benefit	No net benefit	Negative impact	Some benefit
Asia	No net benefit	No net benefit	Negative impact	Some benefit

Strategic implications

- Low renewable energy resources regions only benefit when targeted with high volumes of gas in the post-2040 period. Small volumes of gas have negative impacts and any additional gas provided before 2040 has no emission benefit.
- High renewable energy resource regions are unimpacted by the additional gas supply. This outcome likely reflects that the carbon price is not strong enough in this scenario to induce a high enough share of renewables to require gas as a supporting technology.
- The impact of gas supply on low renewable energy resource regions can be felt globally since it has no impact on high renewable energy resource regions. This is in terms of deployment of high cost renewables, where their deployment is being driven by the low renewable energy resource regions (i.e. not China) after the year 2040.

Summary 4: Increase gas supply to China only

Table 4 Summary of impacts of increase in gas supply to China under the 4DS scenario

	2020-2040		2040 +	
	10% increase	**20% increase**	**10% increase**	**20% increase**
High renewable energy resource region	Increase in emissions from gas. Reduces renewable adoption	Increase in emissions from gas. Reduces renewable adoption	Increase in emissions from gas. Reduces renewable adoption	Increase in emissions from gas. Reduces renewable adoption
Low renewable energy resource region	No change	No change	Supports deployment of high cost renewables	Supports deployment of high cost renewables

Global	Negative impact	No net benefit	No net benefit	No net benefit
Asia	No net benefit	No net benefit	Some benefit	No net benefit

Strategic implications

- Targeting high renewable energy resource regions increases emissions in that region to 2040 as gas is not replacing coal, but rather renewables, under a low carbon price.
- In low renewable energy resource regions, there are substantial benefits for high cost renewable deployment from 2040 onwards with any volume of additional gas in China. However, emissions reduction from increased renewable deployment in low renewable energy resource regions does not offset increased emissions in China so there is no net benefit to Asian or global GHG emissions.

The influence of China

China has a major influence on other regions and the global energy mix. China has the highest level of demand that is growing rapidly, therefore it is constructing a large amount of new capacity. It has unlimited renewable energy resources (relative to its demand), so it does not necessarily need to rely on fossil fuel power generation in the future. The only non-economic limitation we impose is an upper limit on the build rate of technologies.

China has the ability to reduce the cost of technologies through learning-by-doing and the benefits of this cost reduction are shared globally for technologies with a global learning component. This is particularly important for the higher-cost renewables and low-emission technologies, such as concentrating solar power (CSP), offshore wind and gas with CCS. When China builds significant capacity of CSP in some scenarios, this has follow-on impacts for offshore wind in particular, as CSP becomes low cost in all regions and therefore there is only limited construction of offshore wind, which is more expensive. The main flow on from limited offshore wind is felt in India, which has more limited renewable resources and so it chooses to build gas with CCS in the SDS equivalent scenario in order to reduce emissions. However, in the 4DS scenario, China does not need to decarbonise and build CSP, especially when more gas is available so instead Europe leads the way with offshore wind. This reduces the cost of offshore wind, so India can afford it and it no longer builds additional coal-fired power stations.

Key trends

Increase supply of gas is generally only beneficial to GHG emission reduction if it will be used to support high renewable electricity generation shares. Under the modelling presented this does not occur at all before 2040 if the emission reduction signal is weak, such as in the 4DS scenario. There is some indication that this could occur in the post-2040 period of the 4DS scenario (when the carbon price is stronger) so long as the increase in gas is the higher of the two sensitivities explored and the gas is distributed to all Asian markets.

Under the high carbon price of the SDS-equivalent scenario there is a significant shift towards renewable electricity generation and substantial emissions reduction benefits can be achieved from increased gas supply because it is supporting higher renewable shares. The benefit is highest when the gas is provided to a high renewable energy resource region such as China. The higher level of gas increase is preferred if it is not possible to target China only and instead increased gas is sent to all of Asia. Once the transition to renewables is complete, by around 2040, there is no additional emissions reduction benefit from increased gas supply post this period.

In the context of the scenarios examined in this report, gas remains a transitional fuel but perhaps not precisely in the way it was initially envisaged. Gas can assist GHG mitigation during the period when carbon prices or equivalent signals are strong enough to force high renewable electricity generation shares. Until the carbon price reaches that level their impact on emissions reduction is either negative or neutral. After renewables have reached a high share, additional gas supply has nothing further to contribute to emissions reduction.

1 Introduction

LNG supply has been steadily growing over time; its share of the global gas trade (which includes pipeline gas) is expected to increase from the current value of 42% to 60% by 2040 under the IEA's New Policies scenario (IEA, 2018). This increase in supply is projected to also reduce the price of LNG, which will further increase its demand. The major exporting countries are the Middle East, Australia, Sub-Saharan Africa and the USA. Today, the main importers of LNG are Japan and Korea. However, by 2040 the bulk of demand will come from China, followed by Japan and Korea and the rest of Asia (including India).

Natural gas is seen as the 'transition fuel' towards reducing GHG emissions. Under this concept, the use of gas is increased to replace more emissions-intensive coal-fired generation while renewable or other very low emission technologies increase their installed capacity and reduce their cost through learning-by-doing, eventually replacing the need for increased use of gas. Gas is also attractive for reducing local air pollution and is currently lower cost to implement at a system level than renewables for electricity generation in some regions (IEA, 2018). It also has the added benefit that it can provide supporting services for variable renewables, such as solar photovoltaics and wind. Decisions about how soon and to what extent coal, which is a dominant fuel in Asia, should be replaced with gas and renewables in electricity generation are a function of technology, economic and climate policy drivers.

Woodside Energy are considering the development of two new gas basins in Australia (Browse and Scarborough), which would increase the availability of LNG in Asia. Thus, they want to test the assumption through modelling scenarios that an increase in LNG in Asia will lead to a reduction in GHG emissions and support deployment of renewable electricity generation.

2 Methodology

CSIRO's Global and Local Learning Model of the Electricity sector (GALLM-E) has been used to understand the impact of additional LNG on GHG emissions and the Asian electricity sector, under various scenarios where the amount of LNG has been varied over a baseline. The model will be described briefly below followed by the scenarios.

2.1 GALLM-E

GALLM-E has been developed by CSIRO to project the capital cost and uptake of electricity generation technologies. GALLM-E is solved as a mixed integer linear program in which total costs of electricity supply are minimised to reach a given level of electricity demand over time. The model features endogenous technological learning through the use of experience curves at both the global and local scale. The experience curves are segmented into step functions and the location on each experience curve (i.e. cost vs. cumulative capacity) is determined at each time step. The experience curve solution space is non-convex, which means that there are singularities i.e. the solution space is not continuous. However, it is possible to find an optimal, least-cost solution. It also means that any change in any of the parameters that impact the learning curve, such as a change in generation capacity, will result in an entirely new solution space.

GALLM-E has 13 regions based on OECD regional definitions, including current and future expected Asian importers of Australian LNG, namely China, India, Japan, South Korea and South East Asia. It also features 27 electricity generation and energy storage technologies (Hayward & Graham, 2013) (Graham, Hayward, Foster, Story, & Havas, 2018) (Hayward & Graham, 2017) (Brinsmead, et al., 2019). It runs from the year 2006 until 2100 however results are only reported up until 2050 or 2060 due to the much greater level of uncertainty in the input assumptions beyond that date.

GALLM-E includes a "penalty constraint", where in any given year if the new installed capacity of a technology exceeds 1/3 of new demand for capacity, then the cost of that technology will increase. If it exceeds 2/3 of new demand for capacity, the cost penalty is even higher. This constraint is based on supply constraints that have been seen in the past for technologies such as wind and PV, where the price increased as demand increased. The constraint ensures that the model recognises the potential to overheat a technology supply chain, and to some extent this constraint encourages a wide variety of technologies to be deployed. However, if it needs to build more of only one technology it is not prevented from doing so. Similarly, GALLM-E has a market constraint, where again in any given year new capacity of a technology cannot exceed the existing installed capacity by more than 1.55 times, except for emerging technologies where this constraint only becomes active after 3 GW of installed capacity. This constraint avoids rapid and unrealistic sudden increases in installed capacity and the value (1.55) is based on the approximate maximum historical build rates of electricity generation technologies.

GALLM-E has constraints on renewable energy resource availability in India, Japan, South Korea, South East Asia and Western Europe, based on a review of the literature around technical limits of resources, land availability and roof space availability for rooftop solar PV (Hayward & Graham, 2017). This means these countries/regions are limited in their ability to rely solely on renewables for electricity generation and so would benefit from gas-fired over coal-fired electricity generation in terms of reducing GHG emissions. China (and the remaining regions in GALLM-E) have unlimited renewable resources (relative to expected electricity demand). There is a limited fossil fuel constraint, where brown coal-fired generation can only be located in a region that contains brown coal (as brown coal is not traded).

Government policies are a key driver of technology uptake in GALLM-E. The main policy lever is a carbon price (described in Section 2.2.1), but there are country and region-specific technology incentives such as forced capacity construction or renewable energy targets.

Key exogenous data assumptions are presented in Table 5.

Table 5 Key exogenous data assumptions and their sources used in GALLM-E

Electricity demand	IEA for the equivalent scenario	(IEA, 2018)
Fossil fuel prices	IEA for the equivalent scenario	(IEA, 2018)
Biomass and uranium prices	CSIRO Australian National Outlook II	(Brinsmead, et al., 2019)
Initial capital costs, operating and maintenance costs and plant fuel efficiencies	From several studies but the majority are from the GenCost project 2018	(Graham, Hayward, Foster, Story, & Havas, 2018) (GHD, 2018)
Fossil fuel emission factors	Australian factors for direct and indirect emissions	(CO2CRC, 2015)
Historical installed capacities	Various sources most notably the IEA and the United Nations (UN)	(IEA , 2008) (UN, 2013) (UN, 2014)
Government policies	Various sources, majority from the IEA	(IEA, 2018)

More information on the exogenous data assumptions and GALLM-E can be found in (Brinsmead, et al., 2019).

2.2 Scenarios

2.2.1 Carbon prices

Two carbon price scenarios, SDS-equivalent and 4DS, have been modelled. SDS refers to the Sustainable Develop Scenario developed by the IEA and is designed to achieve the Paris Climate Target goals i.e. keep global warming to well below 2-degrees (IEA, 2018). Our SDS-equivalent scenario uses a carbon price trajectory that results in GHG emissions consistent (and slightly below) the IEA's SDS scenario. We also force coal-fired plants that were installed prior to 2006 (i.e. were present as installed capacity when the model starts in 2006) to retire earlier than their expected 50-year lifetime.

The 4DS scenario is more like a 'business as usual' scenario in that it has a carbon price consistent with that outcome and it also has stated and committed government policies to reduce GHG emissions.

The carbon price trajectories are shown in Figure 1 under the SDS-equivalent scenario and Figure 2 under the 4DS scenario

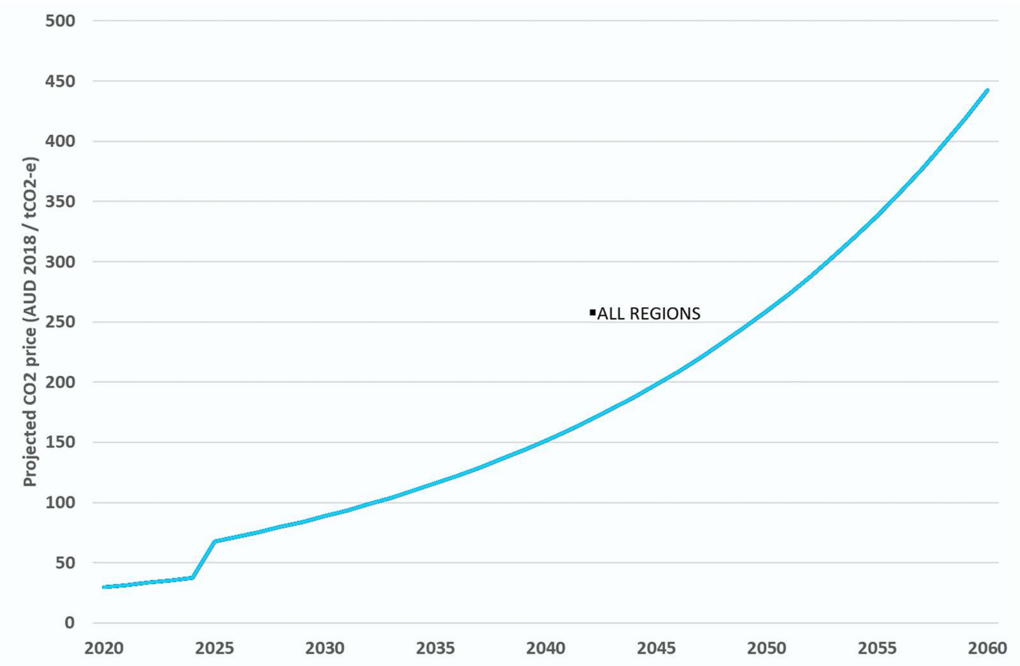

Figure 1 Projected carbon price trajectory under the SDS-equivalent scenario

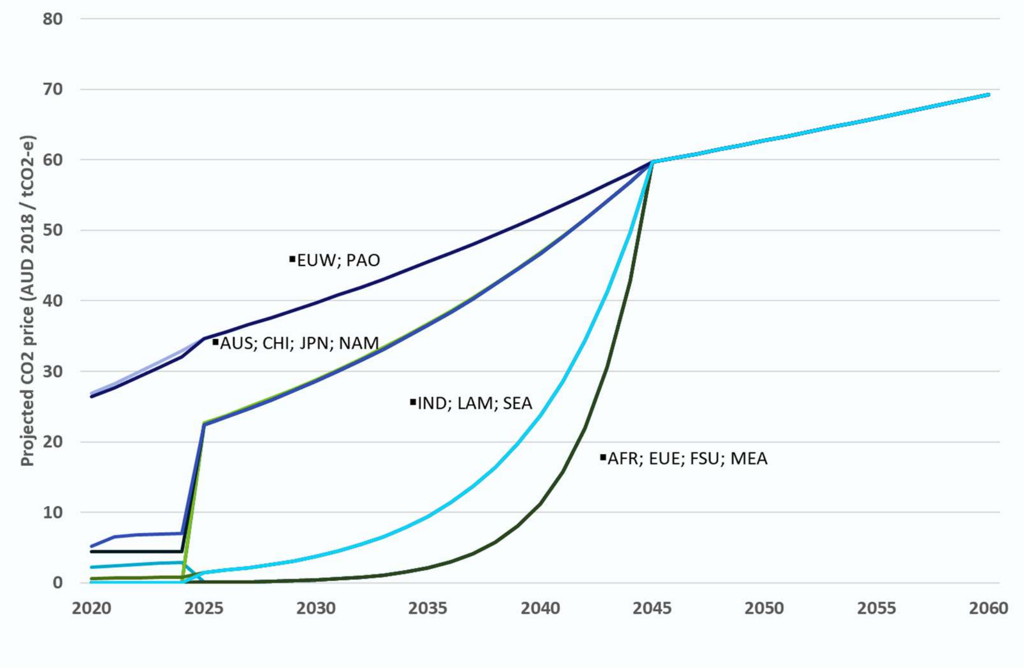

Figure 2 Projected carbon price trajectory under the 4DS scenario. AFR=Africa; AUS=Australia; CHI=China; EUE=Eastern Europe; EUW=Western Europe; FSU=Former Soviet Union; IND=India; JPN=Japan; LAM=Latin America; MEA=Middle East; NAM=North America; PAO=South Korea and New Zealand; SEA=South East Asia

2.2.2 Gas availability in Asia

Five scenarios were constructed which were run under each carbon price trajectory, to explore the impact of different levels of LNG on not just Asian but also global GHG emissions and the uptake of renewable energy.

1. Baseline: this scenario was modelled in Graham et al., (2018). Demand for LNG and gas-fired electricity generation is based on the existing model assumptions.
2. Increase gas supply to all Asian markets by 10%. The Asian gas supply was increased by 10% each year relative to the Baseline and then the model endogenously determined which Asian regions would use the additional gas for electricity generation.
3. Increase gas supply to all Asian markets by 20%. As above but the supply was increased by 20% relative to the Baseline.
4. Increase gas supply to China by 10%. Chinese gas supply only was increased over the Baseline level by 10%.
5. Increase gas supply to China by 20%. As above but by 20%.

The Asian scenarios (scenarios 2 and 3) were designed first as there was no prior expectations about where increased gas supply should be directed. Under the SDS-equivalent scenario in particular, we expect coal-fired electricity generation will become more expensive and thus it makes sense that increased gas will be used in any Asian country. However, we later designed the China scenarios (scenarios 4 and 5) based on observing results of Scenarios 2 and 3, namely that the more gas that was available for countries/regions with unlimited renewable energy resources the higher the deployment of renewables (i.e., gas acting as the supporting technology to renewables). We targeted China because it is the largest region of this type. Also, because of its size in terms of new generation capacity deployment, it also plays a leading role in technological development.

3 Results

Results will be presented by key region and for the world. Results for the whole of Asia combined are presented in Appendix A . Given the linkages between regions in the model in terms of technology learning and installed capacity, a change in one region can result in changes in all regions. This is particularly the case for regions which have a high demand for electricity, namely China. Therefore, it is also important to look at the global picture.

Given that we want to understand the impact additional gas can have on renewable electricity generation, coal-fired generation and GHG emissions, the results will focus on those outcomes. There are some technology differences within the broad category of 'renewables', which will be highlighted.

3.1 SDS-equivalent scenario

3.1.1 Increase gas supply to all Asian markets

The results presented in this section include the Baseline and Asian scenarios (scenarios 2 and 3 described in Section 2.2.2).

Global

The projected global GHG emissions, renewable share of electricity generation and coal share of electricity generation are shown in Figure 3 - Figure 5 respectively. Global GHG emissions under the Baseline and 10% Asian scenarios are similar, however the 20% Asian scenario has lower GHG emissions until around 2022 when the emissions are equivalent under all scenarios. The reason for this difference can be seen by the increase in renewable electricity generation in Figure 4 and the reduction in coal-fired electricity generation in Figure 5. The Baseline does reduce emissions slightly faster by 2035 than the 10% scenario. This can be seen in the slight increase in renewable electricity generation of the Baseline in 2035. However, emissions from coal are the same in both of these scenarios. Therefore, the difference in emissions is due to the difference in gas-fired electricity generation, where gas is displacing some renewables but not coal.

In the 10% scenario decarbonisation happens later and the addition of gas delays the construction of renewables, such as offshore wind and CSP. It also leads to some additional onshore wind, but this does not offset losses of other renewables. The delay in the construction of renewables leads to greater coal-fired electricity generation, most notably in India. India also uses gas with CCS and in order to build up their installed capacity in gas with CCS they keep the older coal-fired power plants running for longer. Because India is renewable energy resource constrained, gas with CCS can compete with more expensive renewables such as offshore wind.

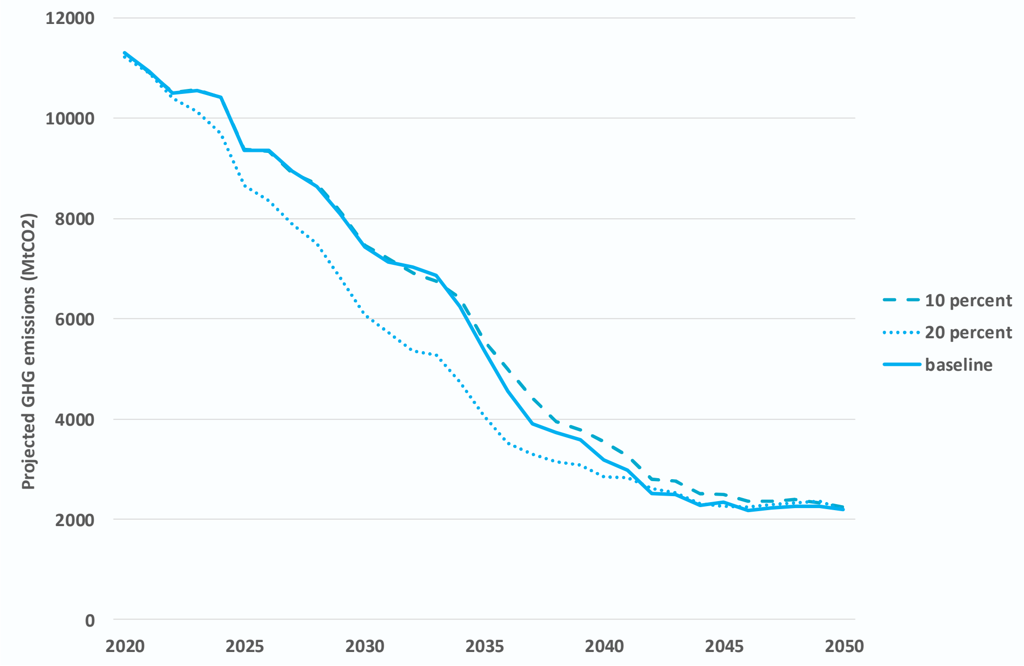

Figure 3 Projected global GHG emissions under the SDS-equivalent and Asian scenarios

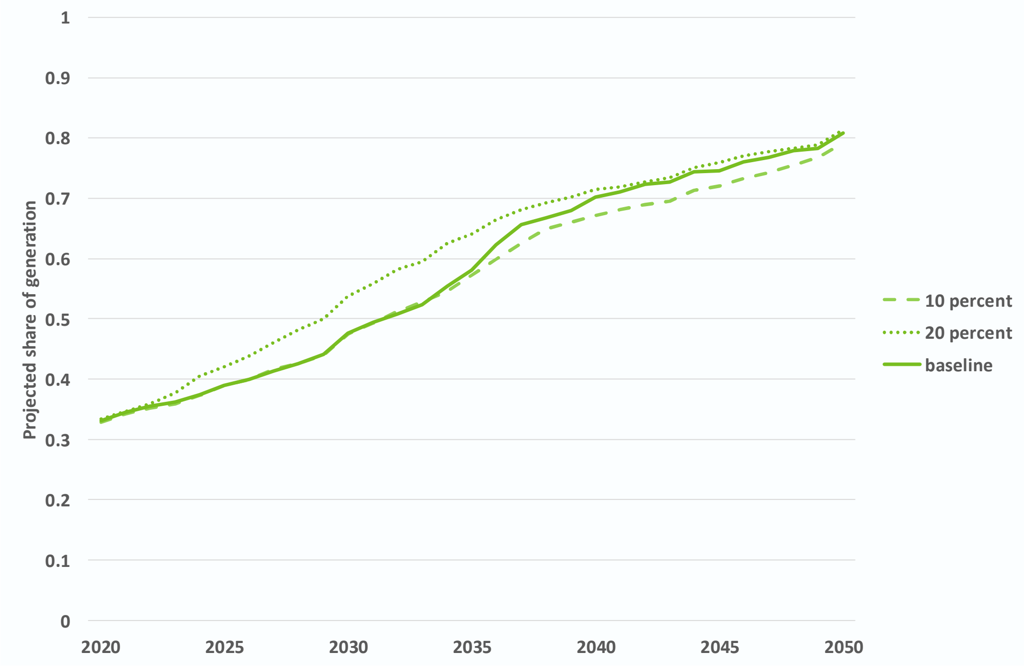

Figure 4 Projected global renewable share of generation under the SDS-equivalent and Asian scenarios

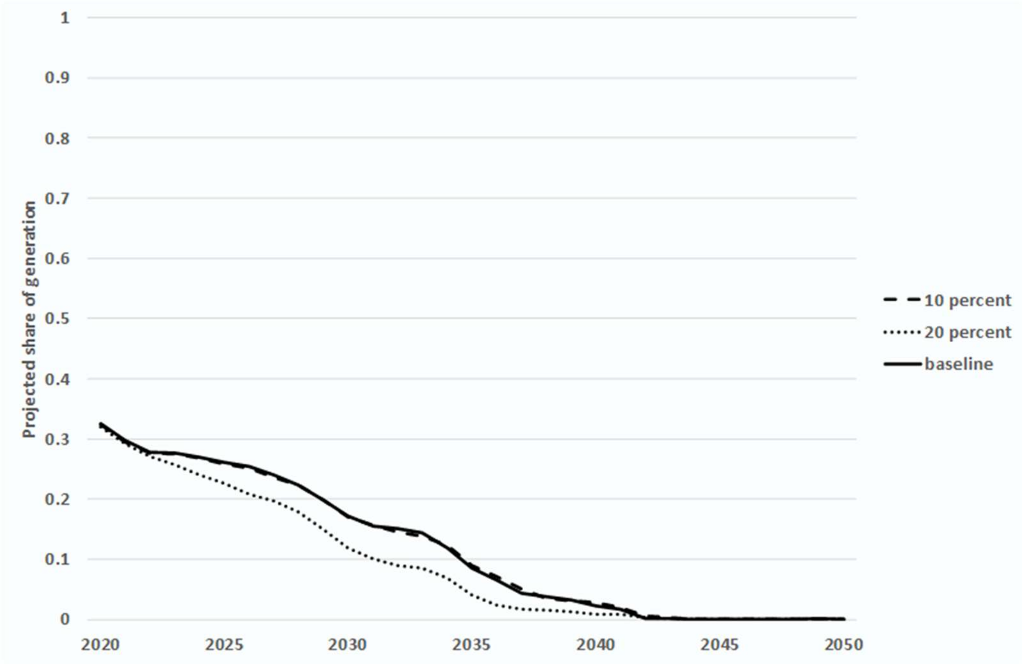

Figure 5 Projected global coal share of generation under the SDS-equivalent and Asian scenarios

China

Projected GHG emissions, share of renewable electricity generation and share of coal-fired electricity generation are shown for China in Figure 6 - Figure 8 respectively. The difference between the 20% Asian scenario and the Baseline and 10% scenarios is much greater in China than globally. GHG emissions level out in China by 2036 under the 20% Asian scenario and by 2043 in the 10% and Baseline scenarios. The emissions profile follows that of coal-fired electricity generation, where it is zero when the emissions level out at below 500 $MtCO_2e$/year. The share of renewable electricity generation increases rapidly from 2022 in the 20% Asian scenario and from 2028 in the Baseline and 10% Asian scenarios. It plateaus at 80% by 2040 in the 20% Asian scenario and 2042 in the Baseline and 10% Asian scenarios. It then increases to 90% at approximately the same rate under all scenarios.

The additional 20% of gas in Asia has resulted in earlier uptake of renewables in China and the rapid reduction in coal-fired electricity generation. The major renewable technologies deployed are onshore wind and concentrating solar thermal, and these are mainly constructed before 2029. For example, China builds 718 GW of new onshore wind capacity between 2015 and 2029 and then 100 GW between 2029 and 2039.

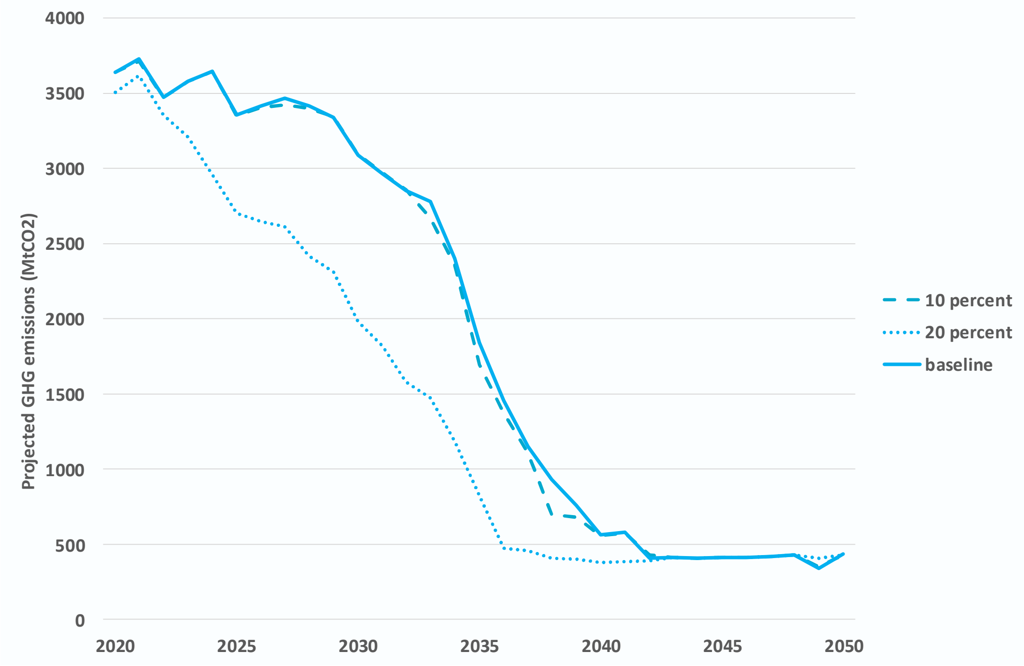

Figure 6 Projected Chinese GHG emissions under the SDS-equivalent and Asian scenarios

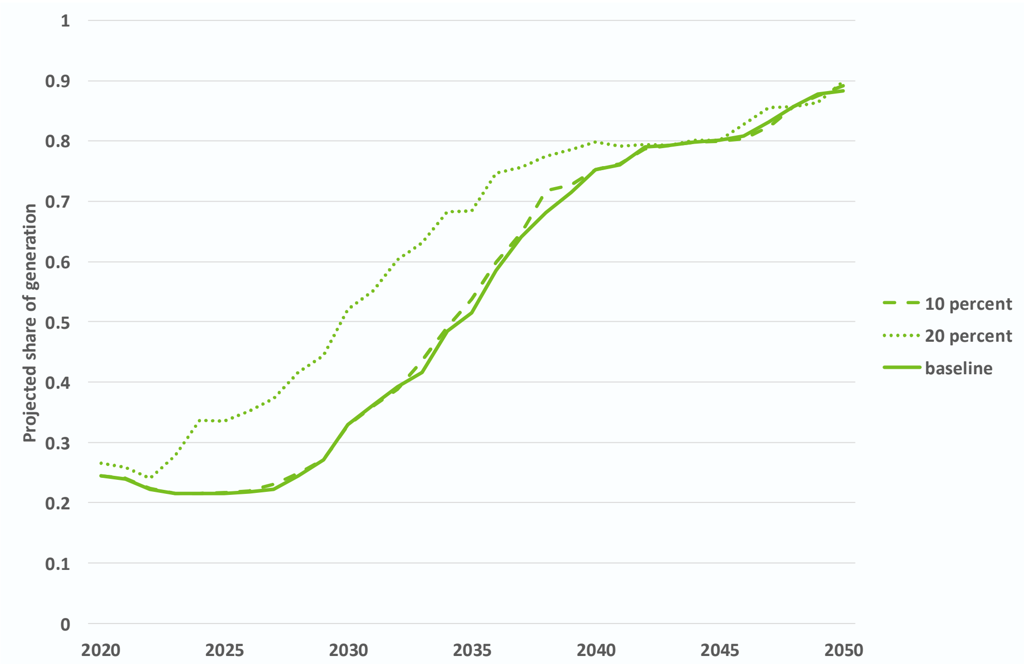

Figure 7 Projected Chinese renewable share of generation under the SDS-equivalent and Asian scenarios

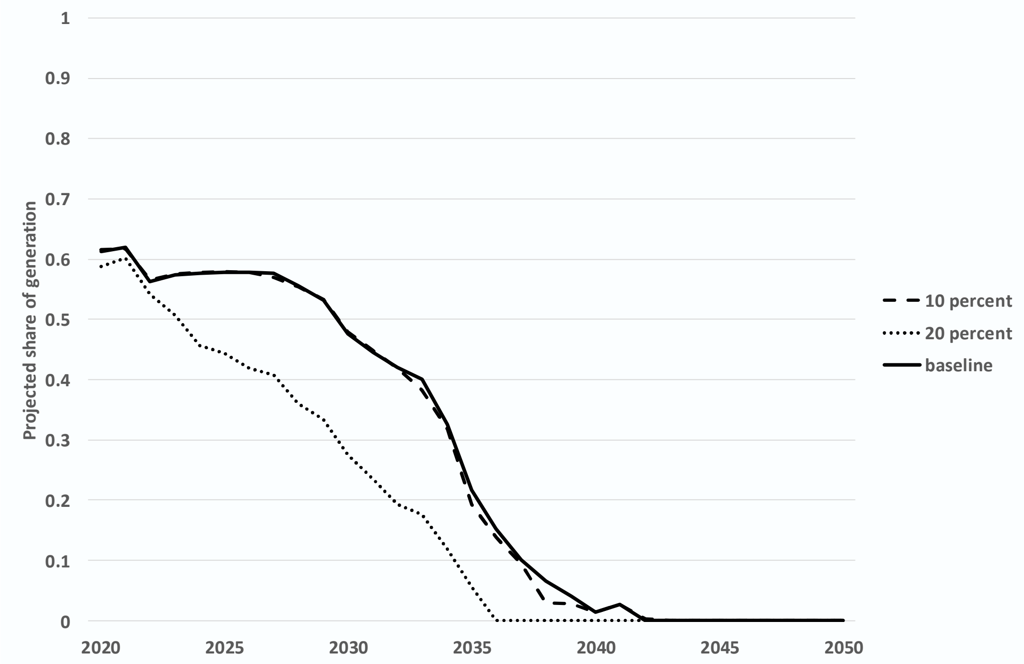

Figure 8 Projected Chinese coal share of generation under the SDS-equivalent and Asian scenarios

India

The projected GHG emission results for India are shown in Figure 9, the projected renewable share of electricity generation is shown in Figure 10 and the projected coal share of electricity generation is shown in Figure 11.

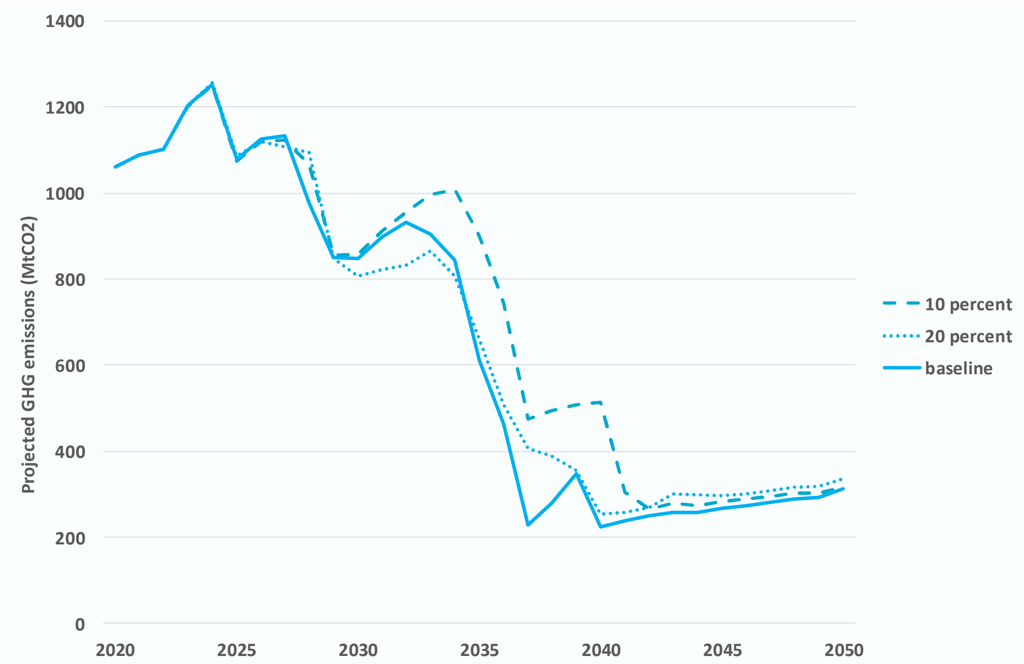

Figure 9 Projected Indian GHG emissions under the SDS-equivalent and Asian scenarios

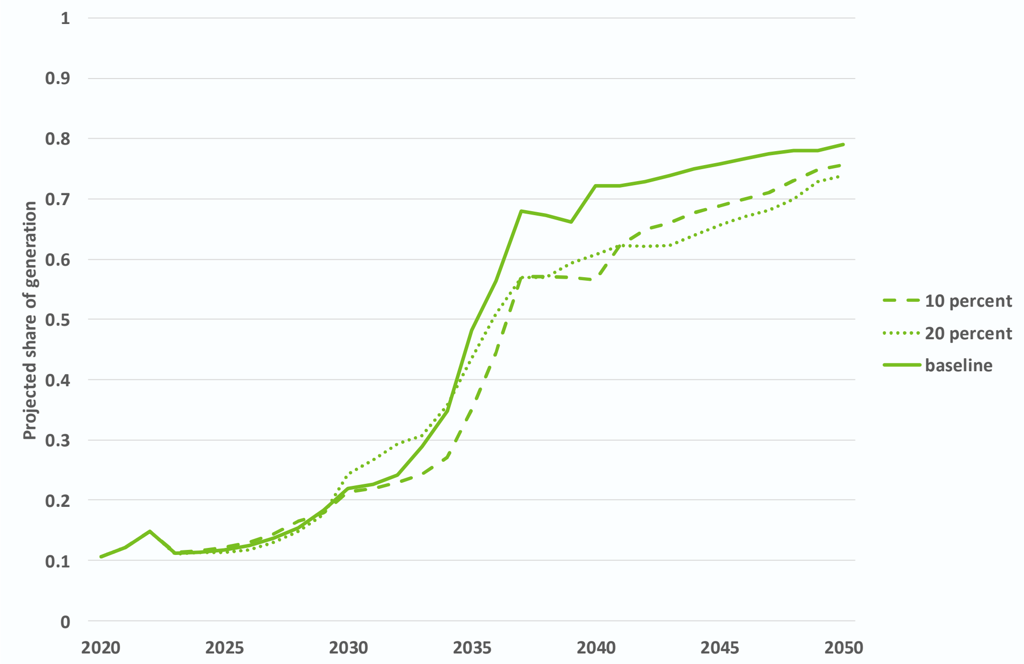

Figure 10 Projected Indian renewable share of generation under the SDS-equivalent and Asian scenarios

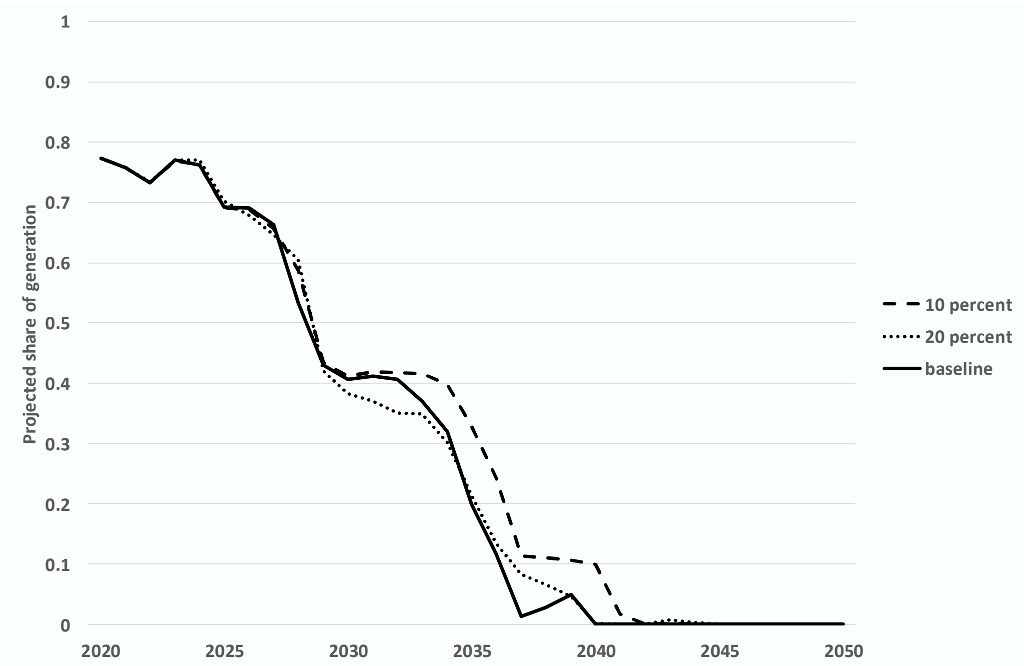

Figure 11 Projected Indian coal share of generation under the SDS-equivalent and Asian scenarios

The results for India do not follow the same trends as the world and China. In terms of GHG emissions, the 10% Asian scenario has the highest emissions between 2030 and 2042 but beyond that there is no clear trend in the results. The Baseline and 20% Asian scenarios are the most similar in India rather than the Baseline and 10% scenarios. This means that in terms of GHG emissions, there is no difference from the Baseline when 20% more gas is added into Asia. The Baseline scenario has the greatest share of renewables and it reaches a share of 70% by 2036. Under the Asian scenarios it reaches that share after 2045. The share of coal-fired electricity generation reaches zero by 2040 under the Baseline and 20% Asian scenarios and 2042 under the 10% Asian scenario. This matches the GHG emissions profile.

India constructs gas with CCS instead of higher cost renewables such as offshore wind under the Asian scenarios. This has an impact on GHG emissions, as gas with CCS captures 90% of the GHG emissions and releases 10%. That is why the emissions increase slightly from 2040 onwards in India, as more gas with CCS comes online.

SEA

The results in the South East Asia (SEA) are shown in Figure 12 - Figure 14.

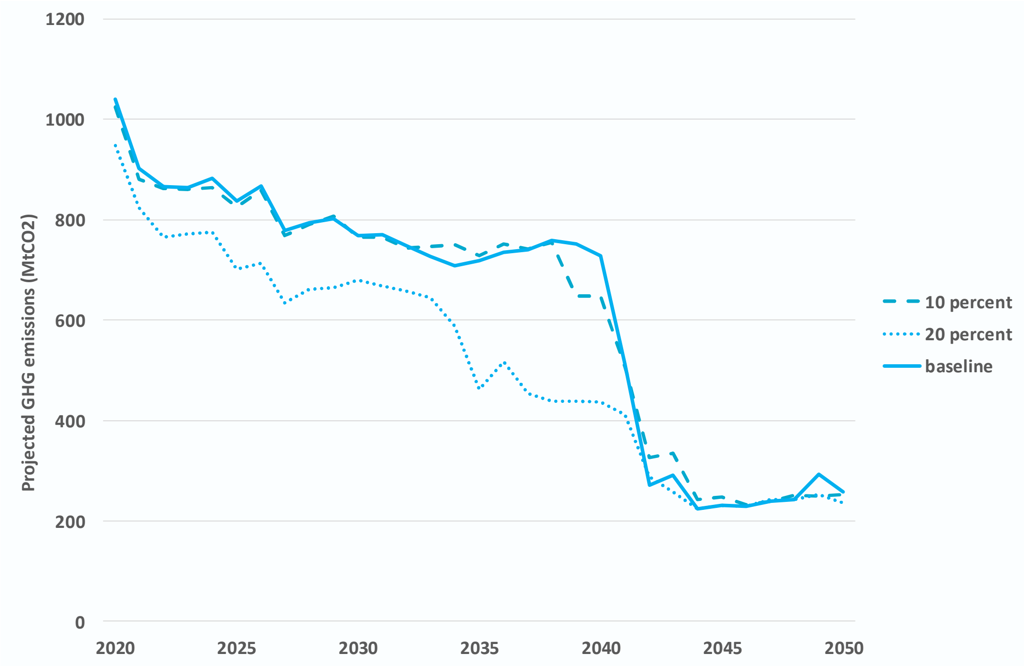

Figure 12 Projected SEA GHG emissions under the SDS-equivalent and Asian scenarios

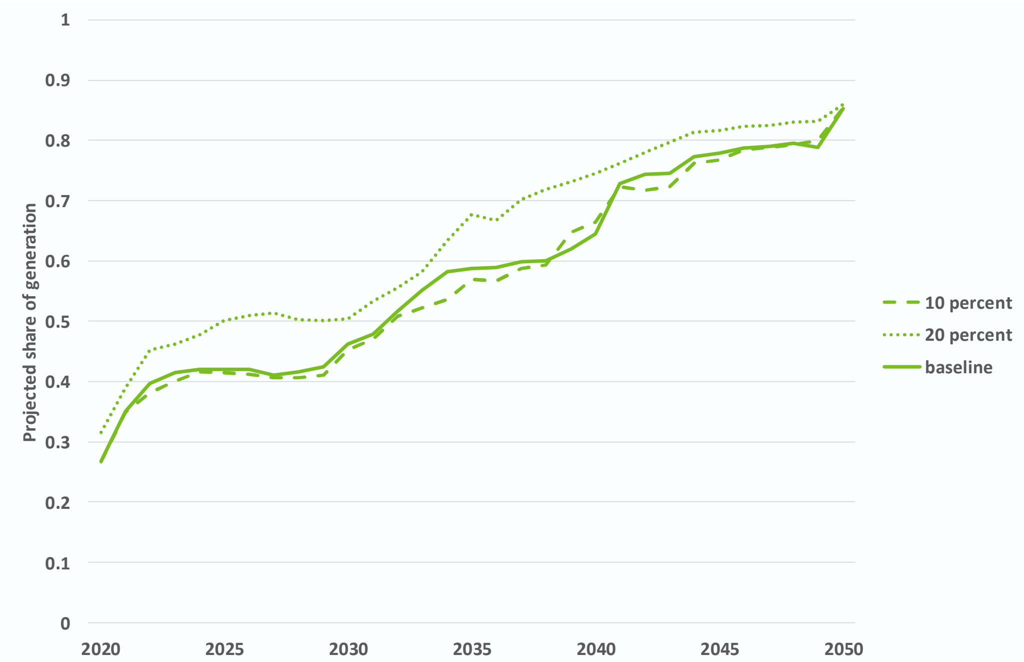

Figure 13 Projected SEA renewable share of generation under the SDS-equivalent and Asian scenarios

Figure 14 Projected SEA coal share of generation under the SDS-equivalent and Asian scenarios

This region has lower demand for electricity than India and China. However, it does have a fairly-large share of coal-fired electricity generation in 2018 – up to 50%. The Baseline and 10% Asian gas scenarios show similar results. However, as can be seen in Figure 14 there is slightly less coal-fired generation up until 2040 when all scenarios are the same. Gas is directly replacing coal in this region under the 10% scenario. The effect is even greater under the 20% Asian scenario, where, like China, there is a period of early rapid emissions reduction and scaling up of renewables. In this scenario, gas and renewables are replacing coal.

3.1.2 Increase gas supply to China

The results presented in this section include the Baseline and China scenarios (Scenarios 4 and 5 described in Section 2.2.2).

Global

The projected global GHG emissions are shown in Figure 15, the projected global share of renewables is shown in Figure 16 and the global projected share of coal-fired electricity generation is shown in Figure 17.

From the year 2025 onwards, the projected GHG emissions are lower under the China scenarios relative to the Baseline. Contrary to the Asian scenarios, the GHG emissions are lower under the 10% China scenario compared to the 20% case. This is reflected in the renewable share of electricity generation, which is greater from 2030 onwards in the 10% China scenario. It reaches 70% renewables by 2036 whereas the Baseline and 20% China scenarios reach it at around 2040. The coal share of electricity generation is slightly different, where there are more similarities between the two China scenarios than the Baseline for coal. This means that gas is replacing coal whether 10% or 20% of gas is added, but the emissions reduction is not as great when there is 20% gas availability due to the additional emissions from gas in China.

The main renewable technology replacing coal in China is onshore wind. By 2028 690 GW of new wind capacity is projected to be built in the 10% China scenario and 440 GW in the 20% case. By 2039 this has increased to 970 GW and 571 GW in the 10% and 20% cases respectively. This rapid early uptake of wind and reduction in coal-fired electricity generation leads to the significant reduction in emissions compared to the Baseline observed in the year 2030. This expansion of wind comes at the expense of other renewable technologies which are not constructed to the same extent between 2029 and 2039 compared to the Baseline scenario, namely large-scale solar PV and offshore wind. In the 20% gas case there is significant construction of CSP: 309 GW by 2029 and 350 GW by 2039. This is not in China, but in SEA, Africa, Europe and North America. Therefore, because there is additional gas in China, in the 20% case, it does reduce the construction of renewable electricity generation compared to the case when only 10% of gas is added.

Gas-fired electricity generation is mixed in these scenarios. There is some gas with CCS but not at the same quantum as in the Asian scenarios. The main technology utilising the additional gas in China is open cycle/peaking plant. This is supporting the deployment of the vast quantities of onshore wind in that region.

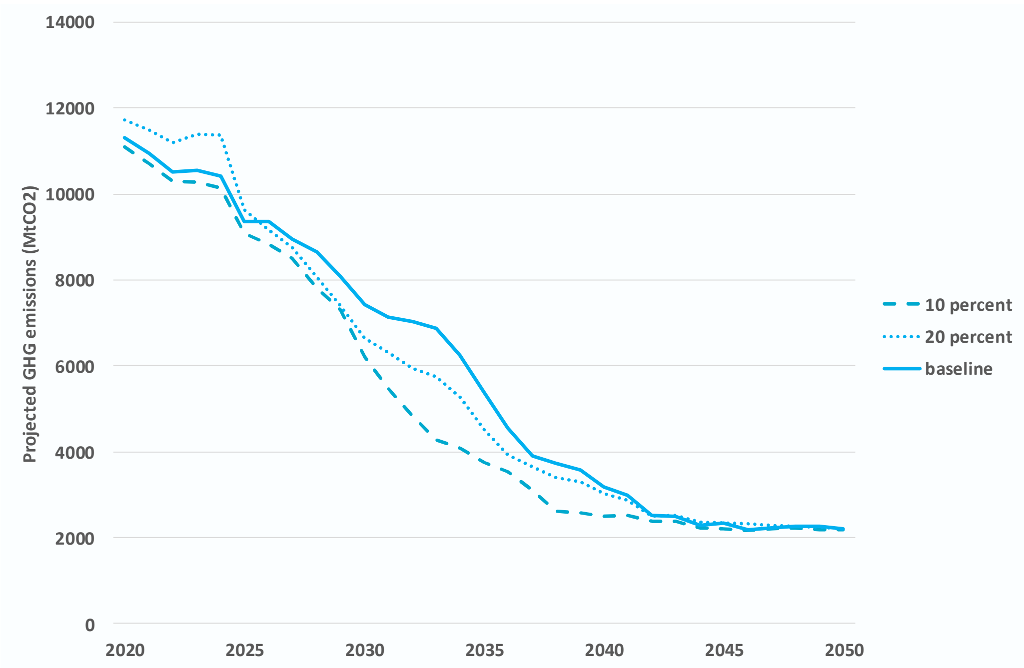

Figure 15 Projected global GHG emissions under the SDS-equivalent and China scenarios

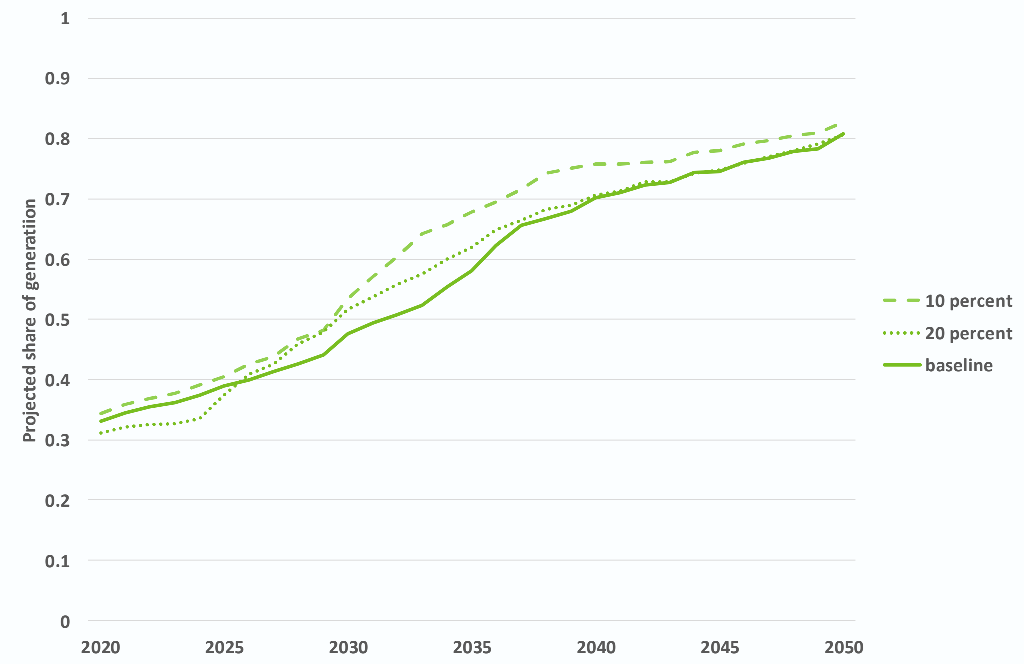

Figure 16 Projected global renewable share of generation under the SDS-equivalent and China scenarios

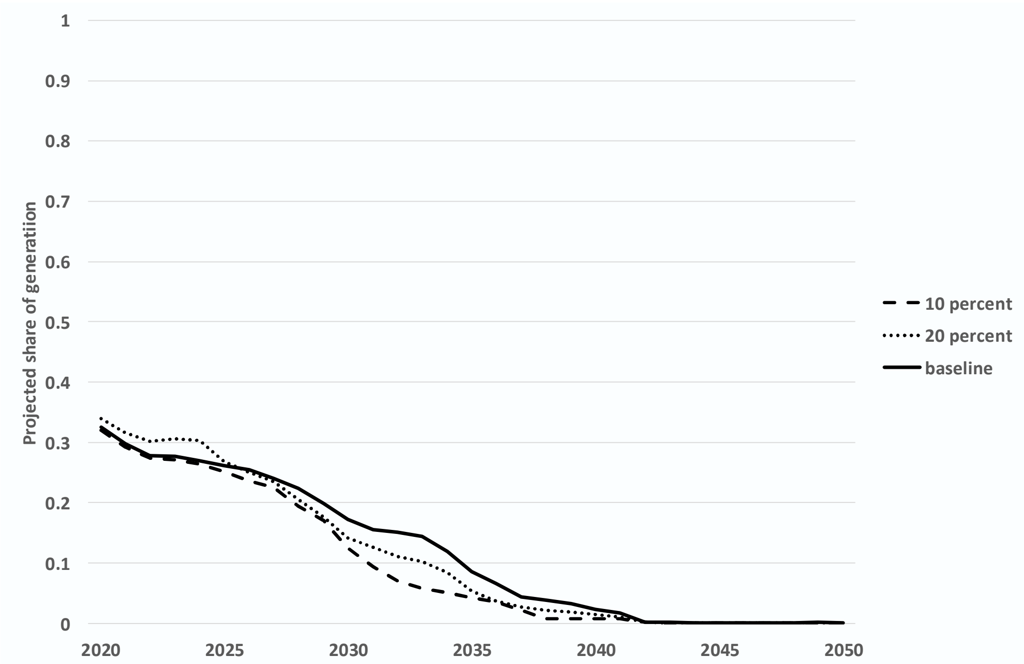

Figure 17 Projected global coal share of generation under the SDS-equivalent and China scenarios

China

The Chinese results are shown in Figure 18 - Figure 20. The trends are similar to the global results but there are larger differences between the Baseline and China gas scenarios. The 10% China scenario clearly has lower GHG emissions than the Baseline and 20% China scenario, but the 20% China scenario is also significantly lower than the Baseline. The emissions profile perfectly matches that of coal-fired electricity generation.

The share of renewables reaches 80% by 2032 in the 10% China scenario and 2045 in the 20% China and Baseline scenarios. After this point in time, all scenarios follow roughly the same trajectory to hit a peak of 90% renewable electricity generation just before 2050. The remainder of the emissions are due to gas peaking plant and gas with CCS.

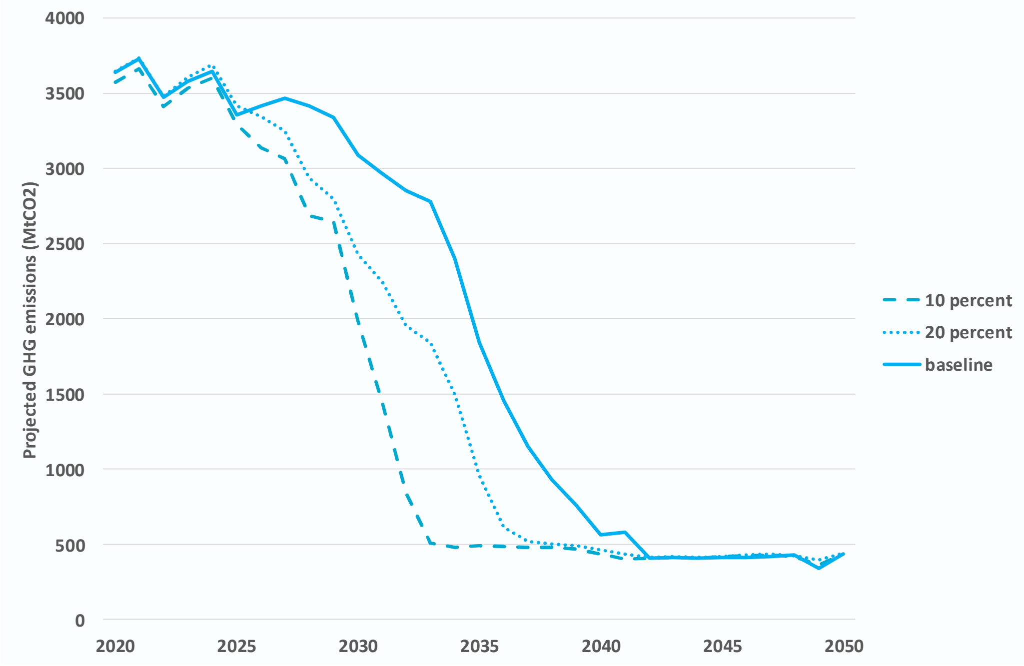

Figure 18 Projected Chinese GHG emissions under the SDS-equivalent and China scenarios

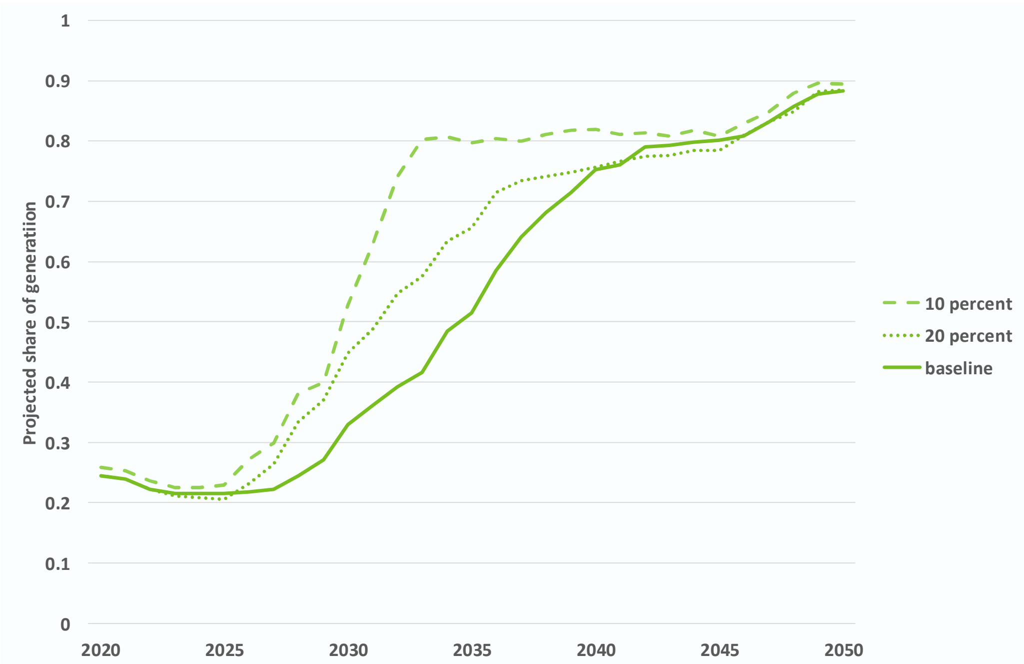

Figure 19 Projected Chinese renewable share of generation under the SDS-equivalent and China scenarios

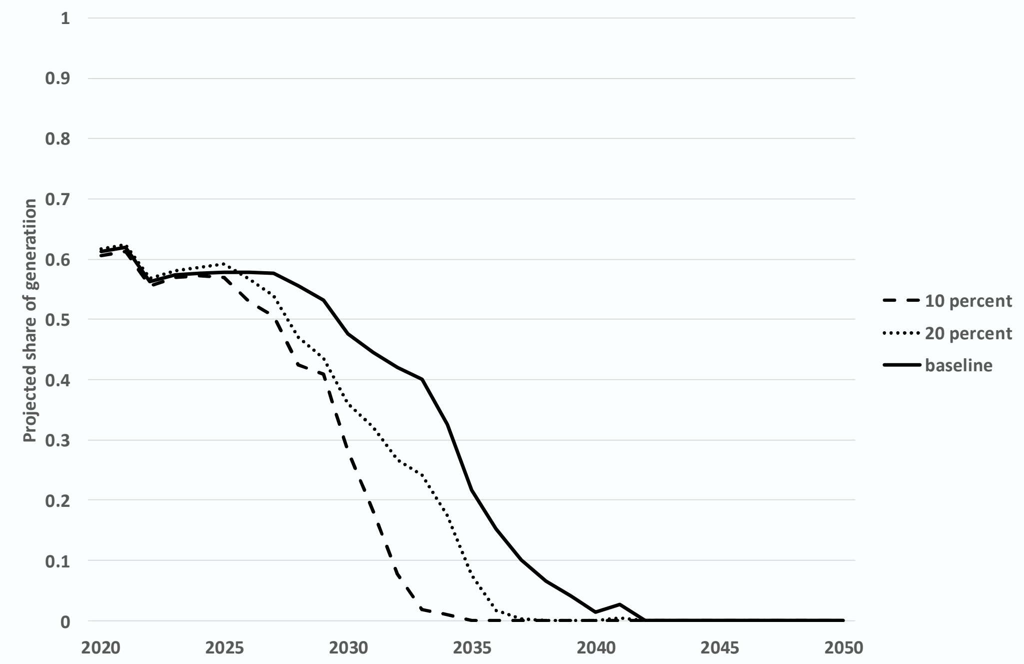

Figure 20 Projected Chinese coal share of generation under the SDS-equivalent and China scenarios

India

The results for India are shown in Figure 21 - Figure 23. The GHG emissions are very similar under all China scenarios except between 2037 and 2041 where emissions are higher under the 20% scenario. As can be seen in Figure 22, the share of renewable generation is lower than the Baseline and 10% scenarios from 2037 until 2050. The reason for this is that there is a continuation of coal generation in the 10% scenario (see Figure 23) until 2041. Gas with CCS is one of the main low emission electricity generation technologies being deployed, more so under the 20% China scenario and this takes time to build up capacity, thus coal-fired electricity generation continues for a few years longer.

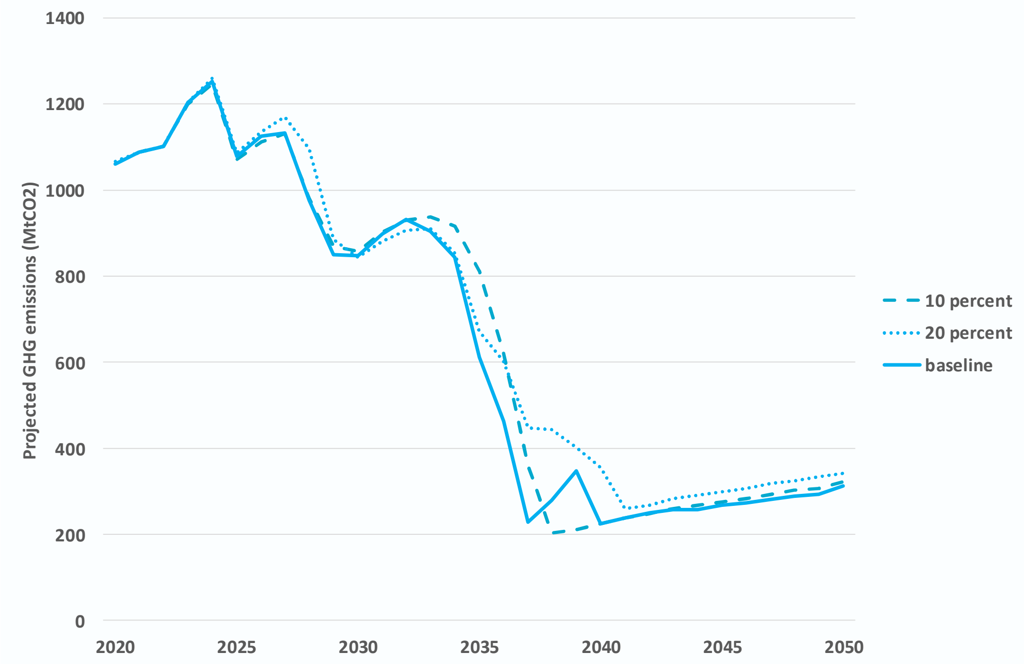

Figure 21 Projected Indian GHG emissions under the SDS-equivalent and China scenarios

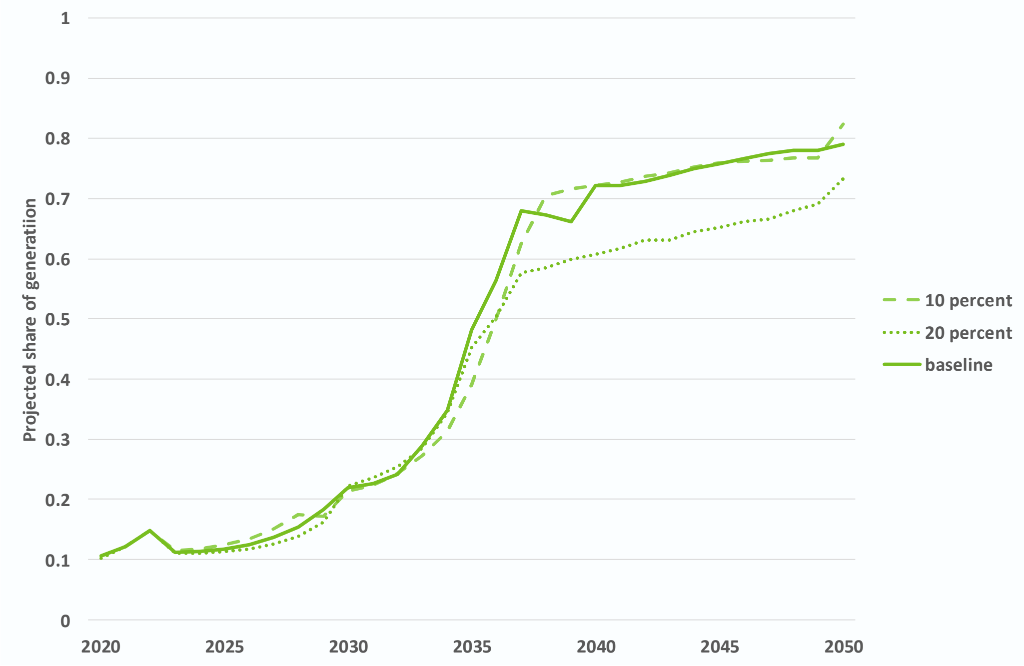

Figure 22 Projected Indian renewable share of generation under the SDS-equivalent and China scenarios

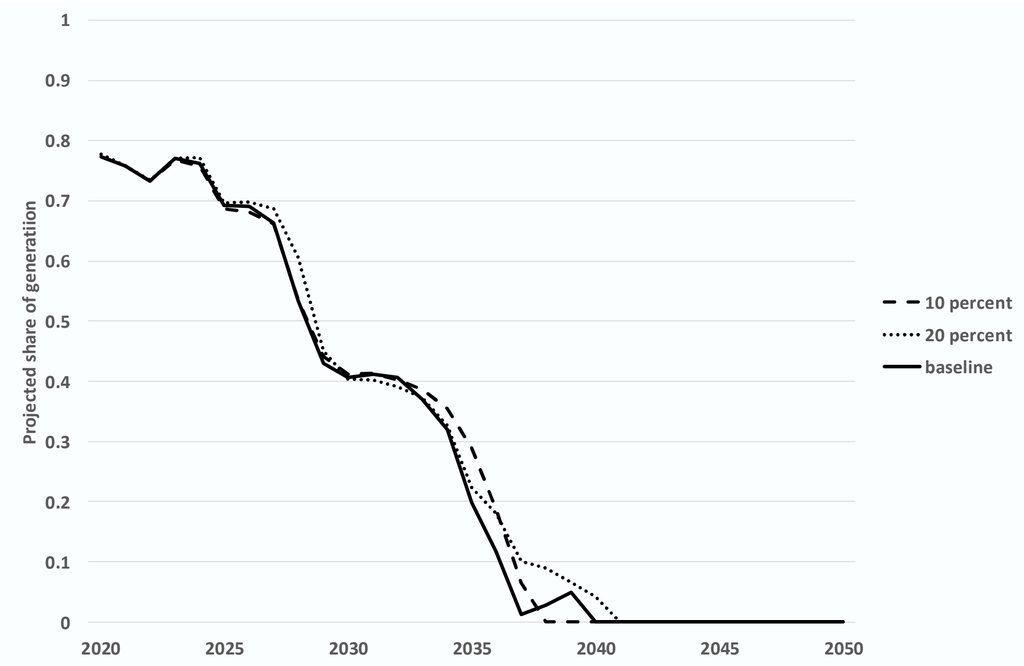

Figure 23 Projected Indian coal share of generation under the SDS-equivalent and China scenarios

SEA

The results for SEA are shown in Figure 24 - Figure 26. The addition of more gas into China has resulted in a reduction in coal-fired electricity generation and emissions and an increase in renewable electricity generation penetration. This impact increases from the 10% to the 20% China scenarios.

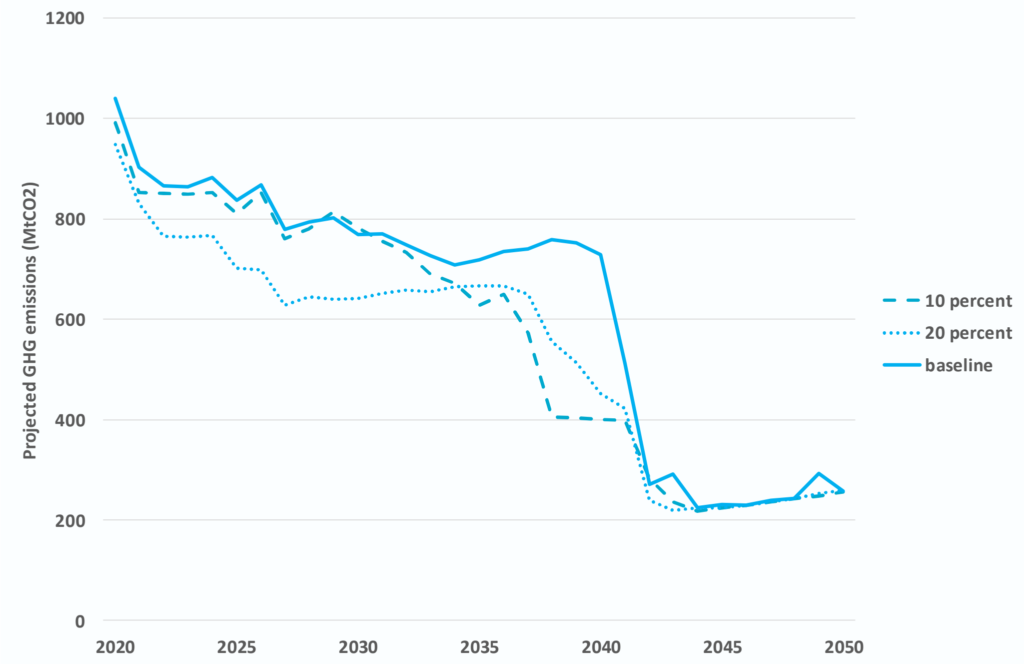

Figure 24 Projected SEA GHG emissions under the SDS-equivalent and China scenarios

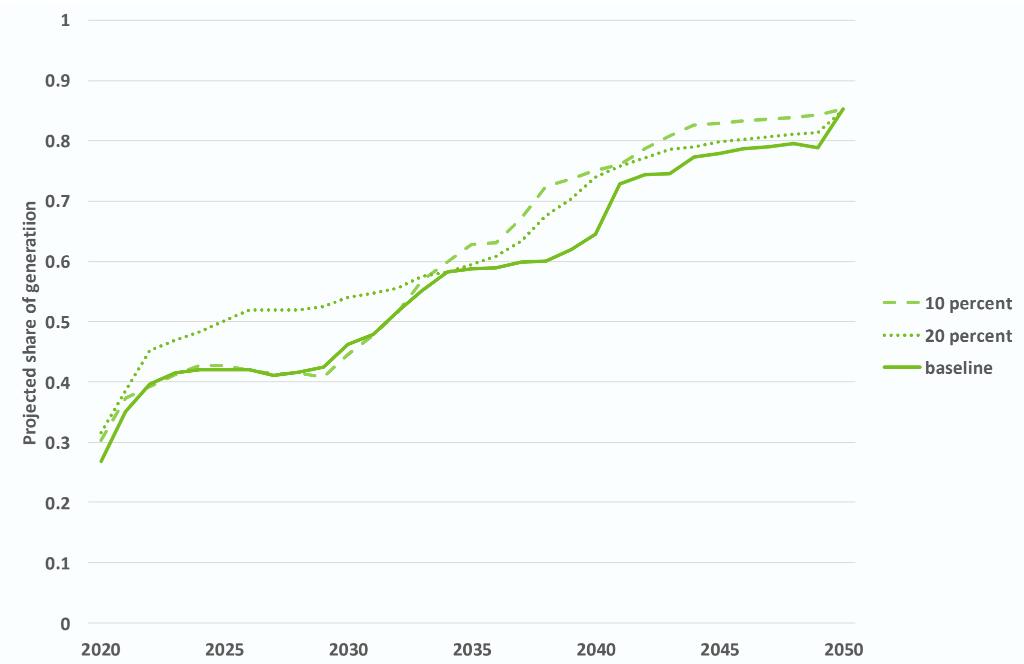

Figure 25 Projected SEA renewable share of generation under the SDS-equivalent and China scenarios

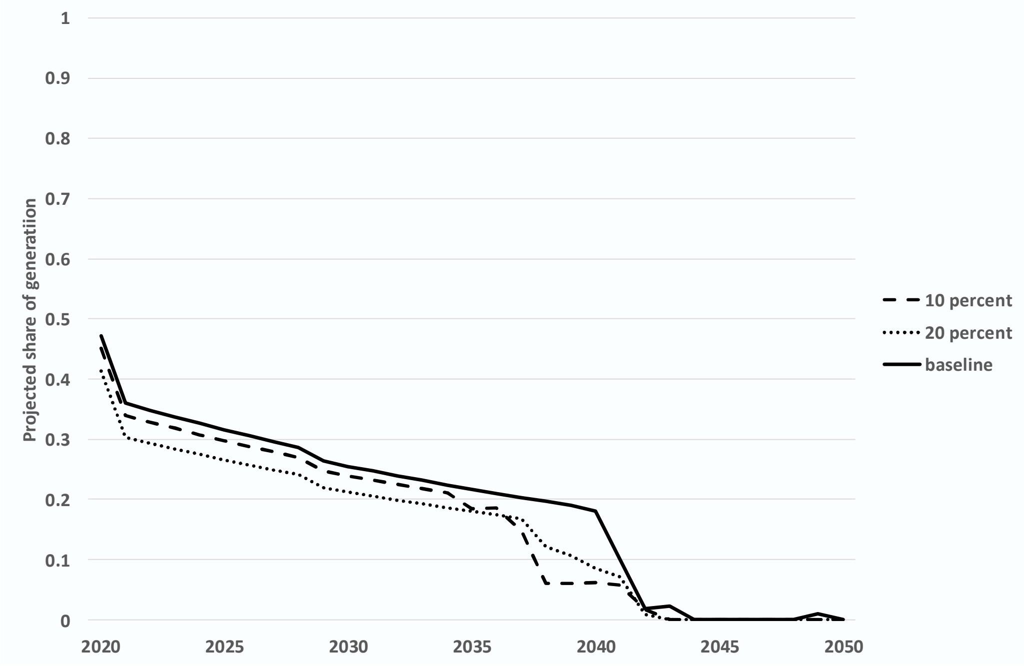

Figure 26 Projected SEA coal share of generation under the SDS-equivalent and China scenario

3.2 4DS scenario

3.2.1 Increase gas supply to all Asian markets

Global

The global projected GHG emissions, renewable share and coal-fired electricity generation share are shown in Figure 27 - Figure 29 respectively.

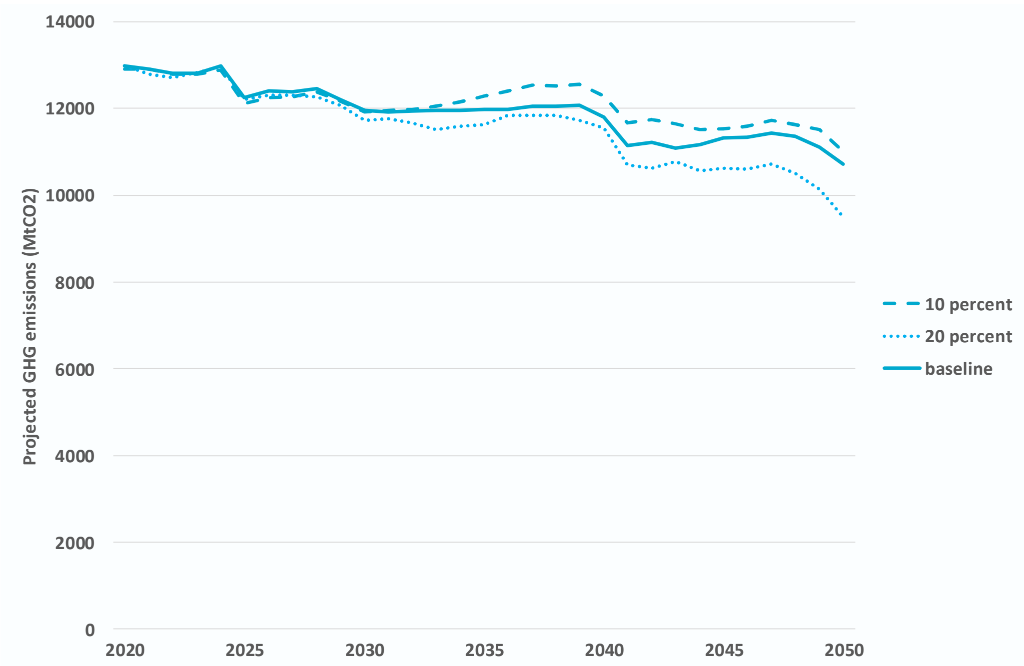

Figure 27 Projected global GHG emissions under the 4DS and Asian scenarios

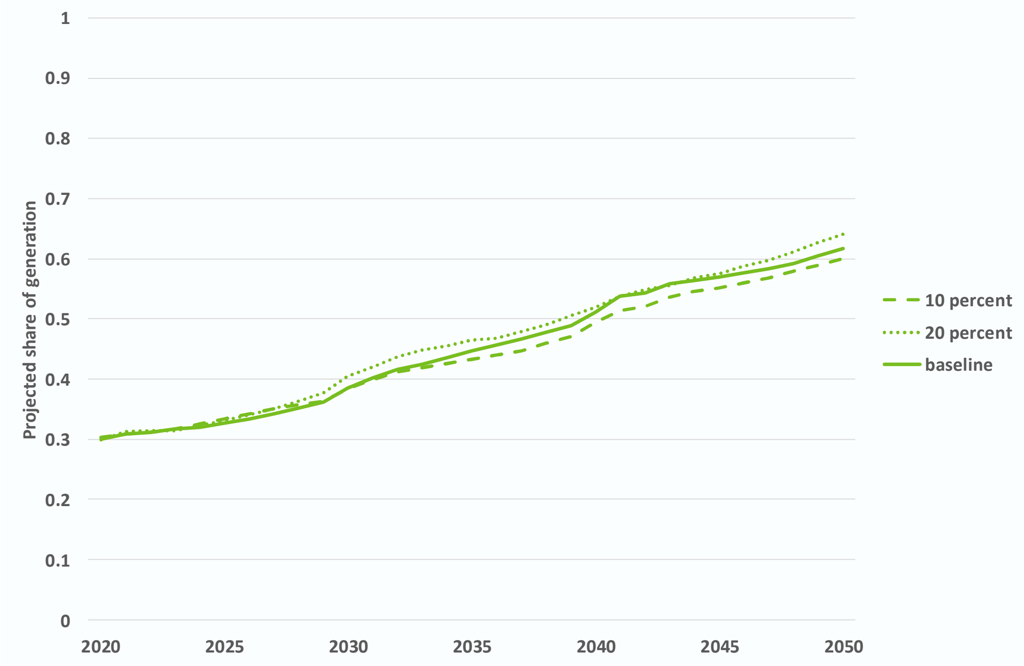

Figure 28 Projected global renewable share of generation under the 4DS and Asian scenarios

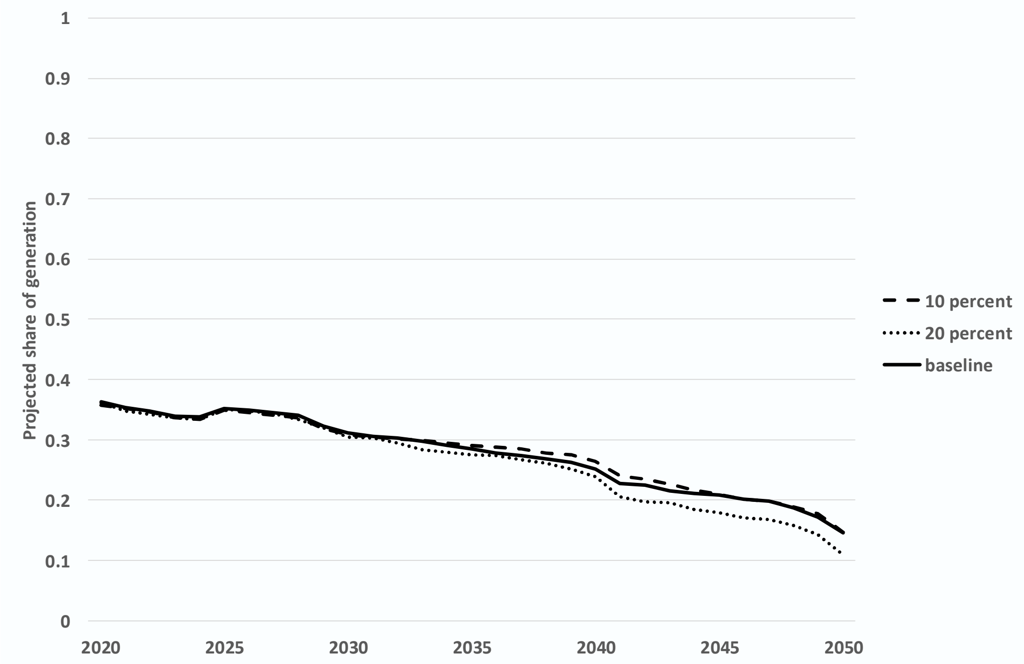

Figure 29 Projected global coal share of generation under the 4DS and Asian scenarios

While the scenarios are very similar in terms of the share of renewable and coal-fired electricity generation, there is a more obvious spread in the GHG emission projections. By 2050 the 10% Asian scenario has higher GHG emissions than the Baseline and this is higher again than the 20% Asian scenario. The difference in GHG emissions is due to the slight differences in renewables and coal-fired electricity generation but also from the increase in GHG emissions from gas. Under the lower carbon price, CCS is uneconomic, thus by adding more gas into the energy mix there are more emissions. In the 10% Asian scenario, gas is not replacing coal-fired electricity generation (see Figure 29) and there are fewer renewables compared to the Baseline (see Figure 28).

Therefore, adding more gas will only increase GHG emissions. However, under the 20% Asian scenario, gas and renewables are replacing some coal-fired electricity generation and thus GHG emissions are lower than the Baseline.

The conclusion is similar to that of the SDS-equivalent Asian scenario, in that a small amount of gas (10%) has no GHG emissions benefit, but a large amount of gas (20%) reduces GHG emissions. However, the result is very different in timing. In the SDS-equivalent Asian scenario, the GHG emissions reduction benefit was only before 2040. In the 4DS Asian scenario the GHG semission reduction benefit is only after 2040.

China

The results for China are shown in Figure 30 - Figure 32. They show that the addition of gas into Asia has no impact on China. Coal-fired electricity generation in particular is completely unaffected. This is to be expected as this is a low carbon price scenario.

Therefore, unlike the SDS-equivalent scenario, China is not using the additional gas being provided to Asia.

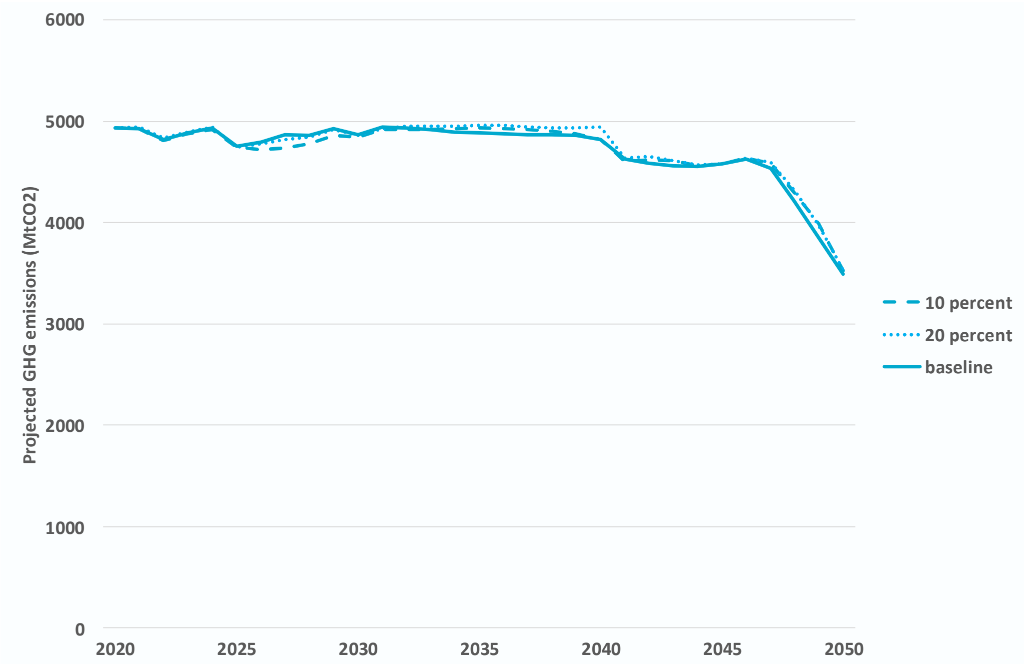

Figure 30 Projected Chinese GHG emissions under the 4DS and Asian scenarios

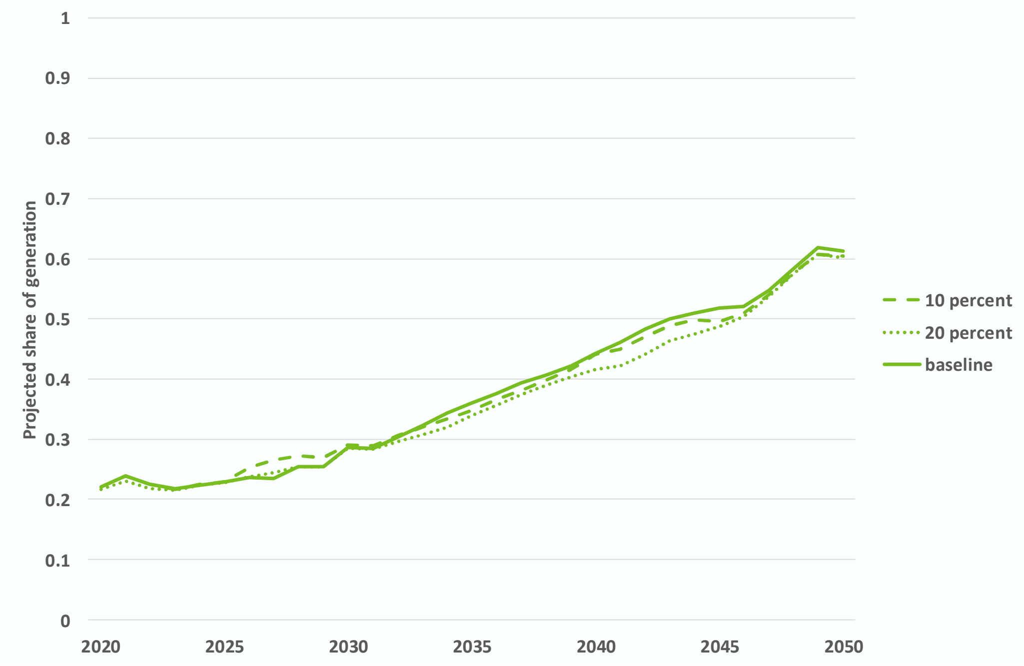

Figure 31 Projected Chinese renewable share of generation under the 4DS and Asian scenarios

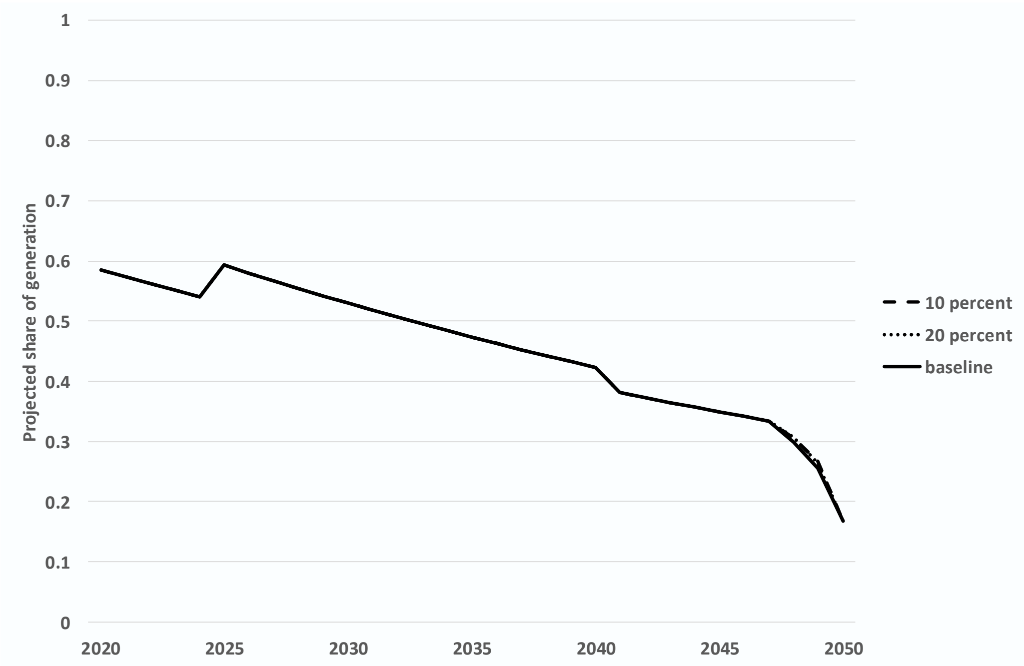

Figure 32 Projected Chinese coal share of generation under the 4DS and Asian scenarios

India

The results for India are shown in Figure 33 -Figure 35. These figures show a departure in results from around the year 2035, where under the 10% Asian scenario GHG emissions increase as the share of coal-fired electricity generation increases and there are fewer renewables, but then under the 20% Asian scenario GHG emissions decrease as does the share of electricity generation from coal and there are more renewables. The Baseline scenario is in the middle. In terms of capacity, under the 10% Asian scenario India builds 46 GW of High Efficiency Low Emission (HELE) coal-fired power plants by the year 2029 and 99 GW less large-scale solar PV and 47 GW less CSP, compared to the Baseline. In the 20% Asian scenario it builds more large-scale solar PV (an additional 31 GW) than the Baseline scenario by the year 2039. This has an impact on the share of renewable electricity generation in this scenario.

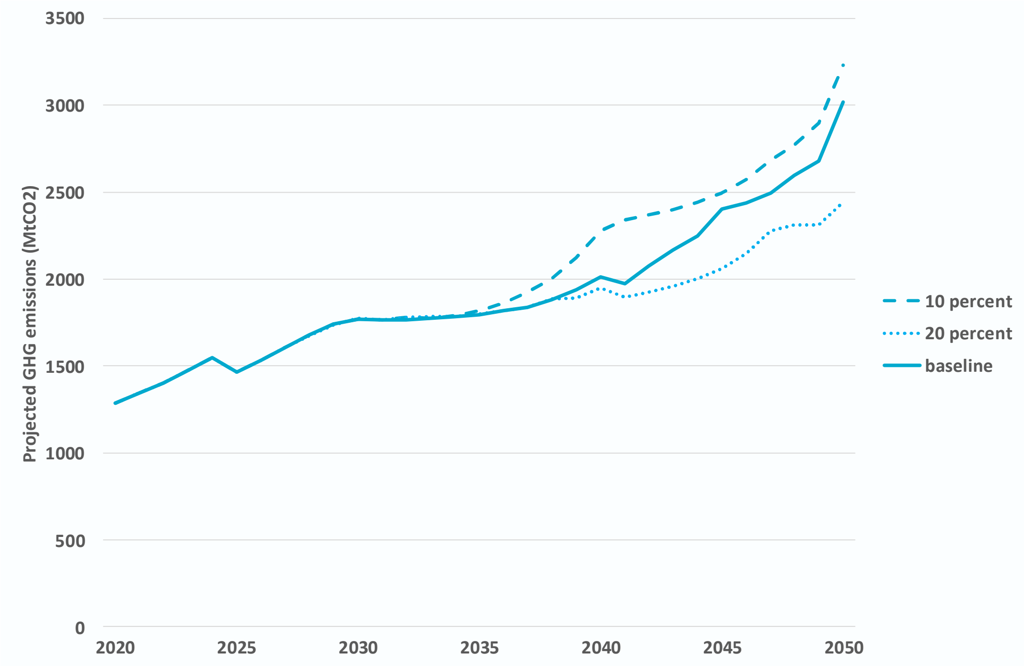

Figure 33 Projected Indian GHG emissions under the 4DS and Asian scenarios

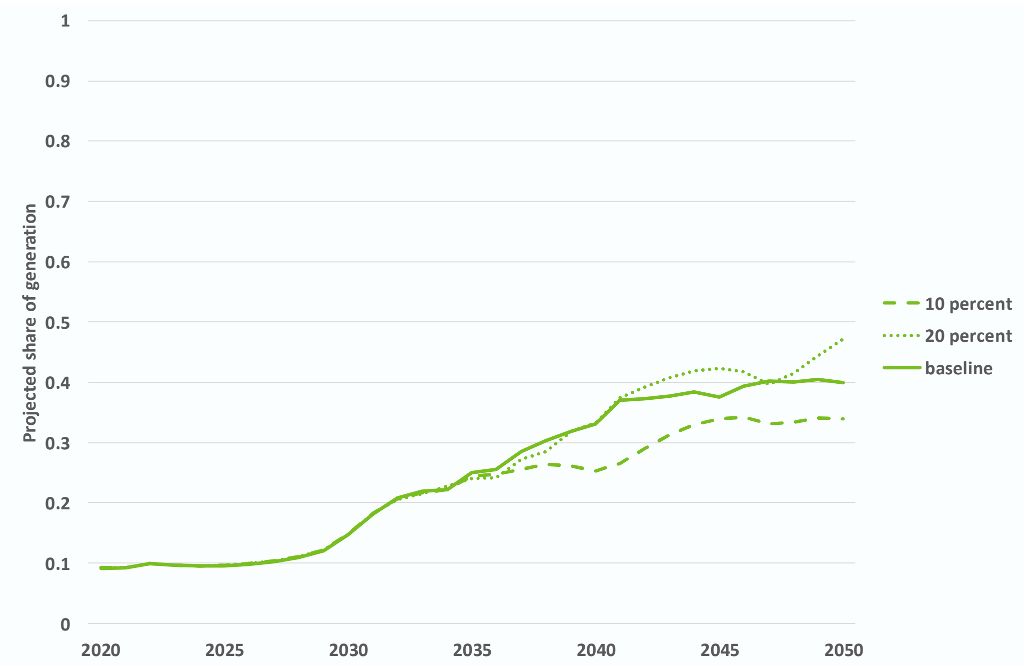

Figure 34 Projected Indian renewable share of generation under the 4DS and Asian scenarios

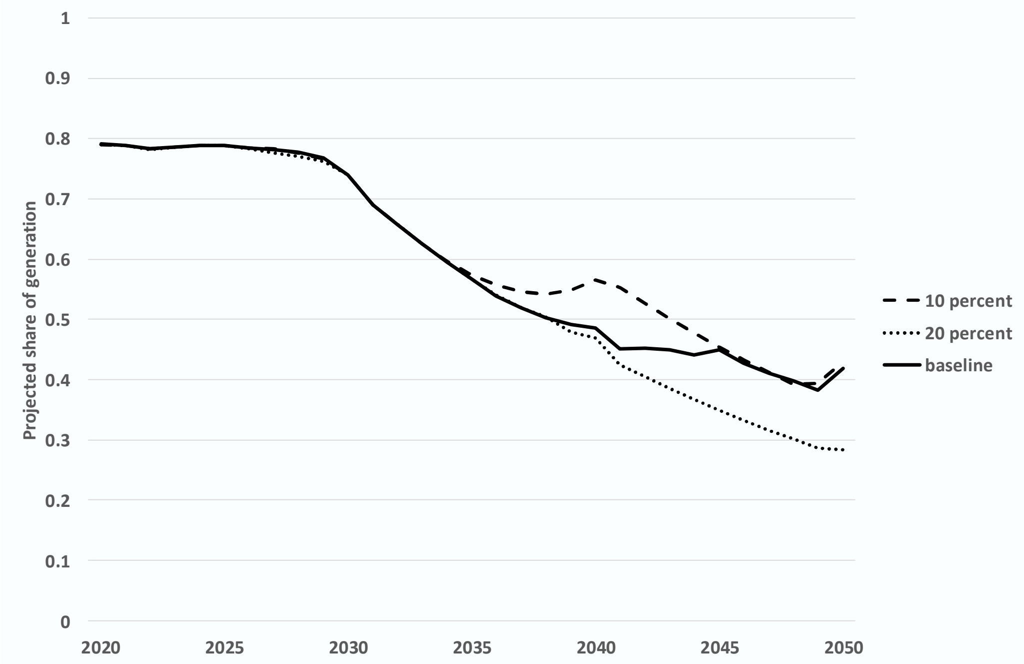

Figure 35 Projected Indian coal share of generation under the 4DS and Asian scenarios

SEA

The results for SEA are shown in Figure 36 - Figure 38.

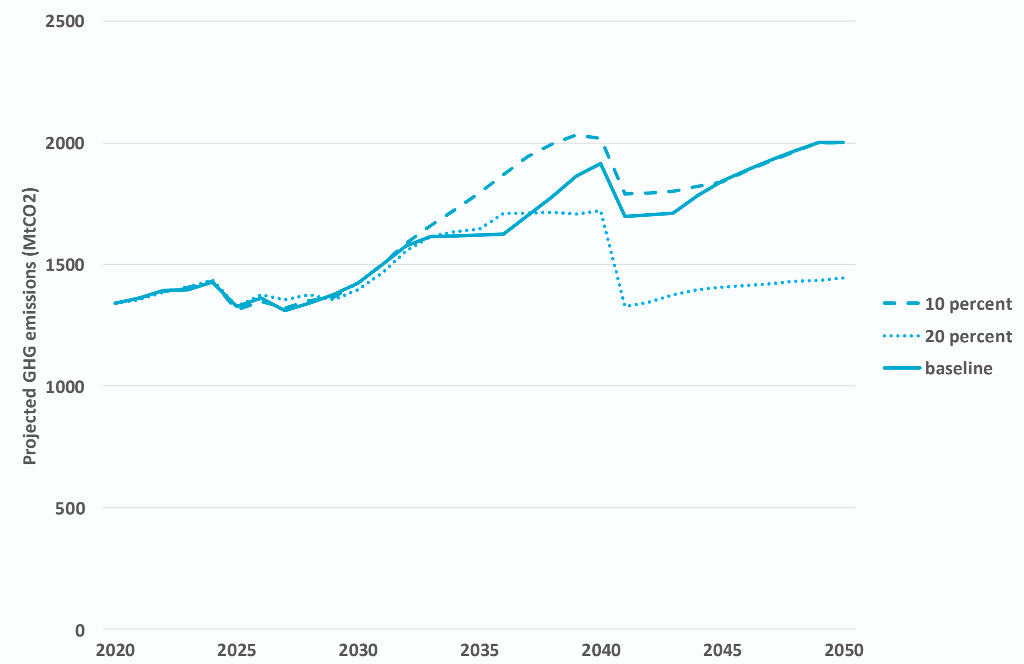

Figure 36 Projected SEA GHG emissions under the 4DS and Asian scenarios

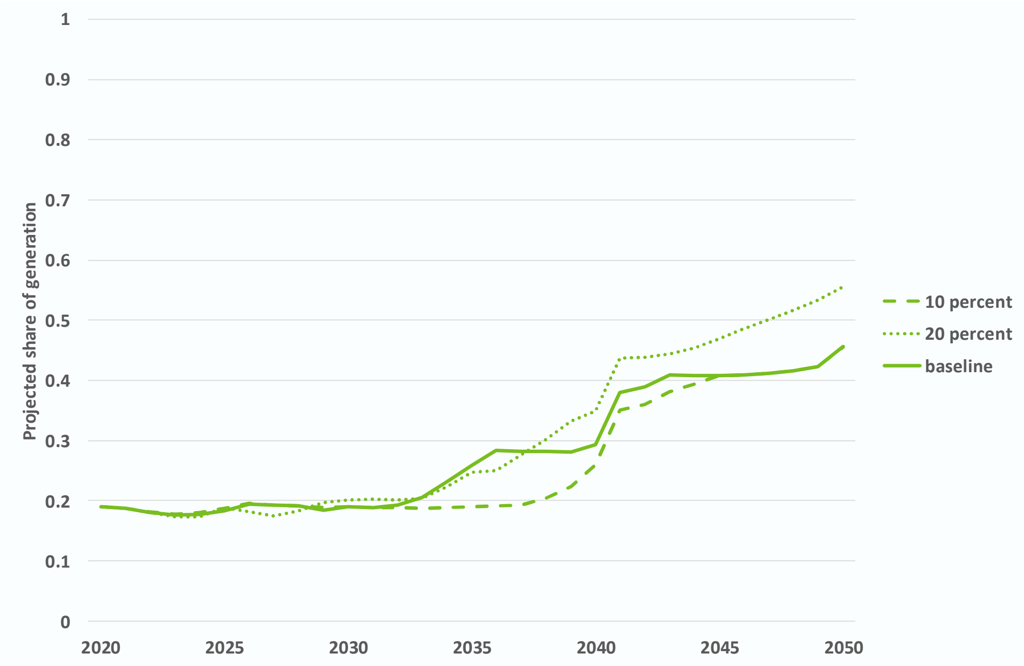

Figure 37 Projected SEA renewable share of generation under the 4DS and Asian scenarios

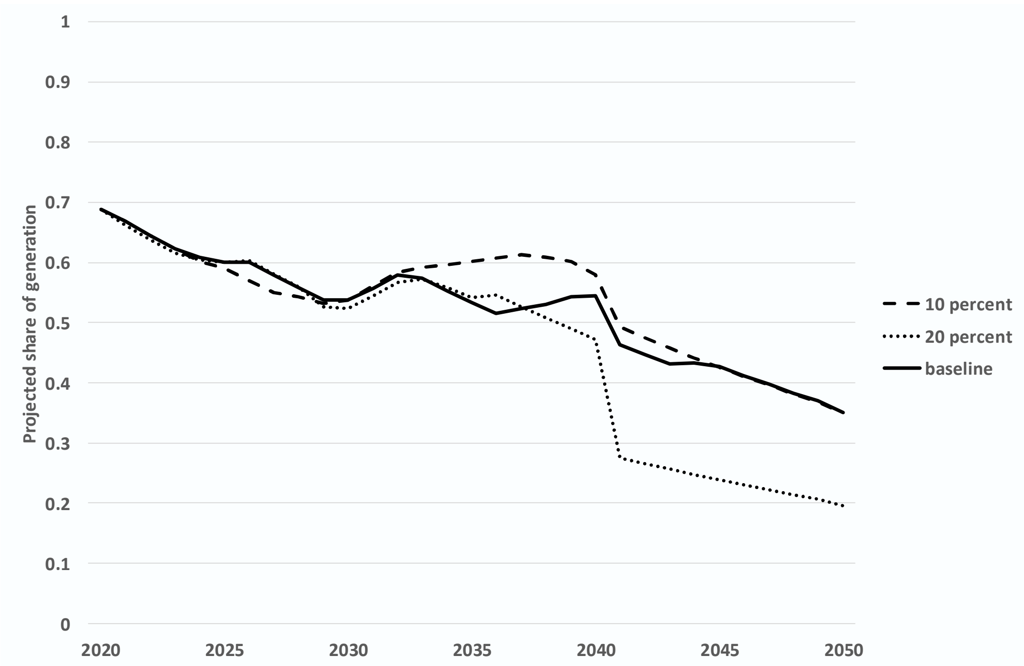

Figure 38 Projected SEA coal share of generation under the 4DS and Asian scenarios

As with India, the highest GHG emissions are under the 10% scenario and the lowest are under the 20% scenario, with the Baseline in the middle. The same goes for the share of renewables, where the highest share is under the 20% scenario, and the share of coal-fired electricity generation, where the 20% scenario has the lowest share. The scenarios start to diverge from the year 2032 and the Baseline and 10% scenarios end up converging again in 2045. The results are largely being driven by coal-fired electricity generation. Under the 10% scenario, 19 GW of additional HELE coal-fired power stations are built by 2039 and at the same time there is 25 GW less hydro, compared to the Baseline. However, in the 20% scenario there is 36 GW less HELE coal built compared to the

Baseline, along with an additional 63 GW of gas combined cycle, 38 GW of hydro and 40 GW of large-scale solar PV by 2039. The combined effect of the reduction in coal and increase in gas and renewables reduces GHG emissions, as can be seen in Figure 36.

3.2.2 Increase gas supply to China

Global

The global GHG emission results are shown in Figure 39, the share of renewable electricity generation is shown in Figure 40 and the share of coal-fired electricity generation is shown in Figure 41.

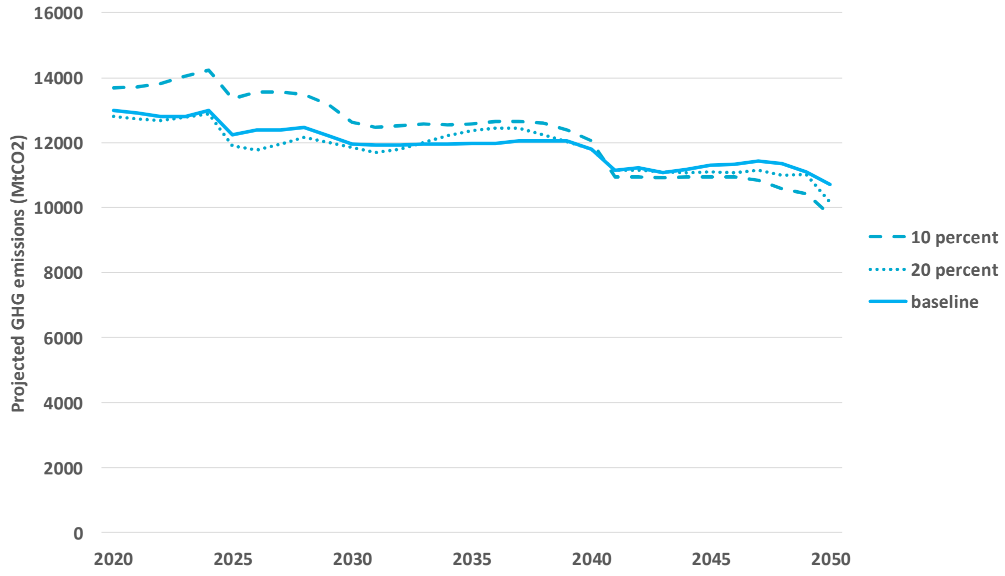

Figure 39 Projected global GHG emissions under the 4DS and China scenarios

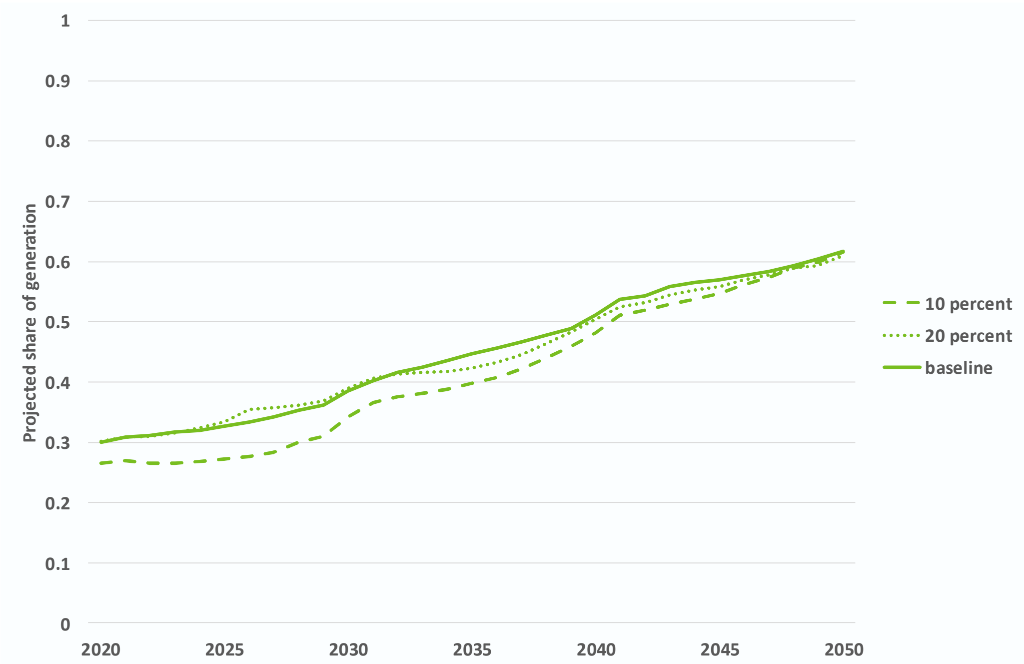

Figure 40 Projected global renewable share of generation under the 4DS and China scenarios

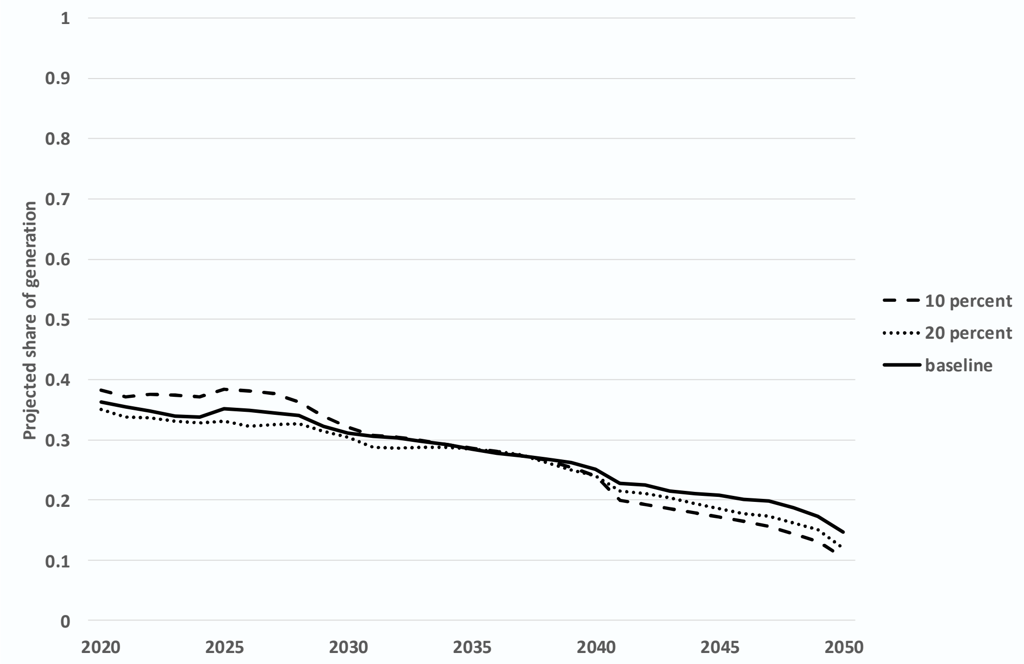

Figure 41 Projected global coal share of generation under the 4DS and China scenarios

There is minimal difference between the scenarios globally. The slight amount of difference occurs from 2020 until 2040, where the 10% scenario has higher GHG emissions, more coal-fired electricity generation and fewer renewables than the Baseline and 20% scenarios.

There are differences within the shares of different renewable technologies, driven by what happens in China. China has policies which force the construction of CSP. This tends to kick-start learning-by-doing and thus cost reductions in this technology. This then results in the uptake of CSP in other regions, such as North America, the Middle East and Europe. However, given that CSP is one of the more expensive renewable electricity generation technologies, the construction of this technology has a negative impact on the other more expensive renewable electricity generation technologies, such as offshore wind. Accordingly, in the Baseline scenario there is more CSP than in the gas scenarios, because gas is forced into China, there is less CSP but more offshore wind in other regions.

China

The results for China are shown in Figure 42 - Figure 44.

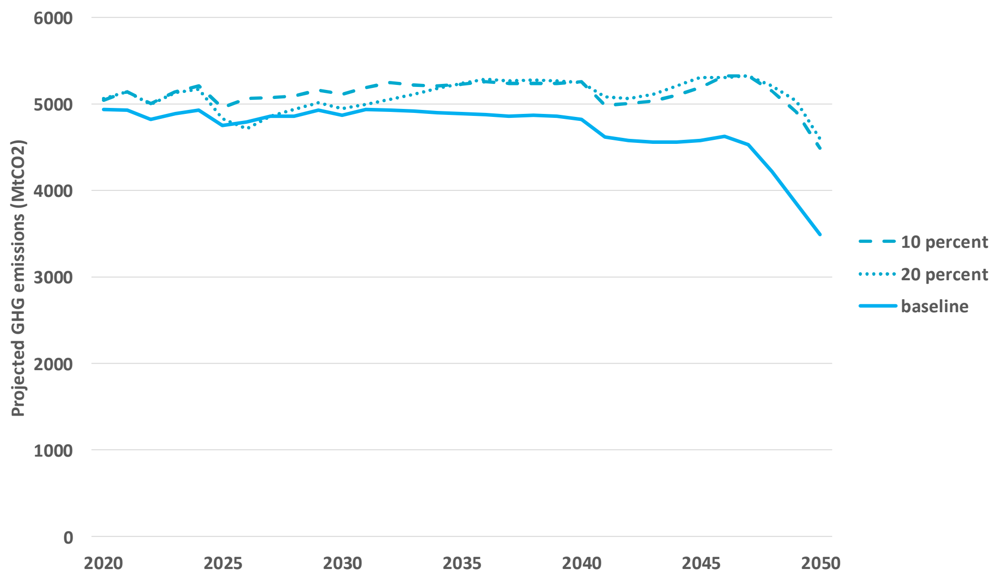

Figure 42 Projected Chinese GHG emissions under the 4DS and China scenarios

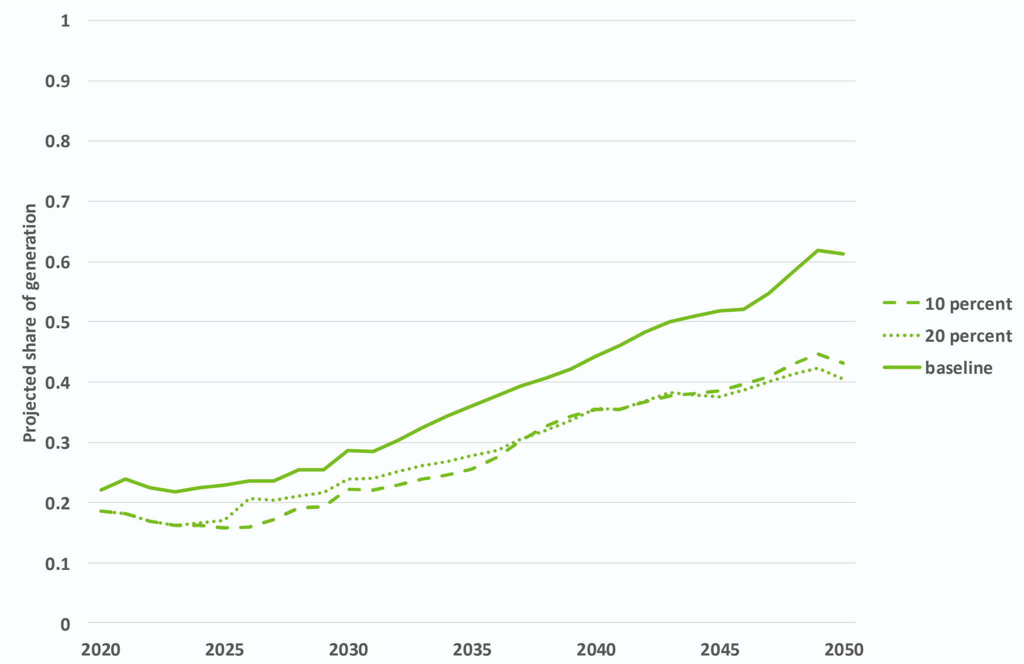

Figure 43 Projected Chinese renewable share of generation under the 4DS and China scenarios

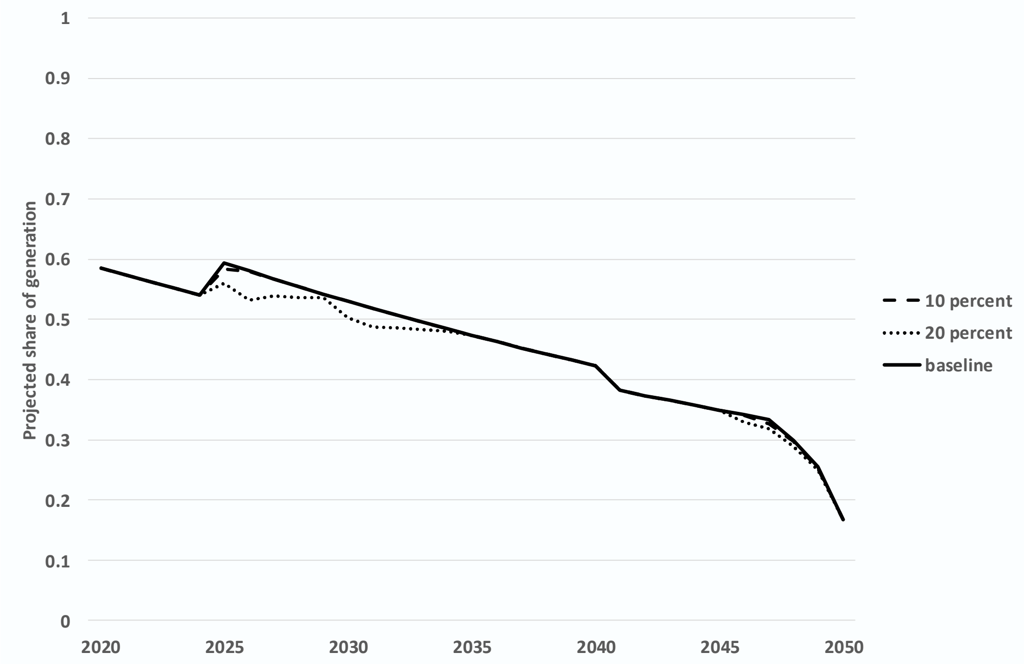

Figure 44 Projected Chinese coal share of generation under the 4DS and China scenarios

The general trends are that the Baseline scenario has the highest share of renewables and the lowest GHG emissions. The share of coal-fired power generation is very similar under all of the scenarios, therefore, the addition of gas into China under the higher carbon price is not replacing coal-fired power generation but rather replacing renewables. China builds more gas combined cycle and gas peaking plants under the 10% and 20% China scenarios and less CSP. CSP is the main form of renewable energy effected by the additional gas. CSP has a higher capital cost than other variable renewables and it can also provide peaking capacity, thus it can be replaced with gas peaking plant.

India

The results for India are shown in Figure 45 - Figure 47. The difference between India and China in terms of the scenario results is quite striking. Whereas with China the highest GHG emissions occurred in the gas scenarios, in India the highest GHG emissions are under the Baseline scenario. As can be seen in Figure 47, the share of electricity generation from coal is higher from 2037 under the Baseline scenario, which increases GHG emissions. At the same time, generation from renewables is lower. India builds 26 GW of HELE coal-fired generation capacity under the Baseline scenario by 2039. In the gas scenarios, India builds offshore wind instead – up to 75 GW.

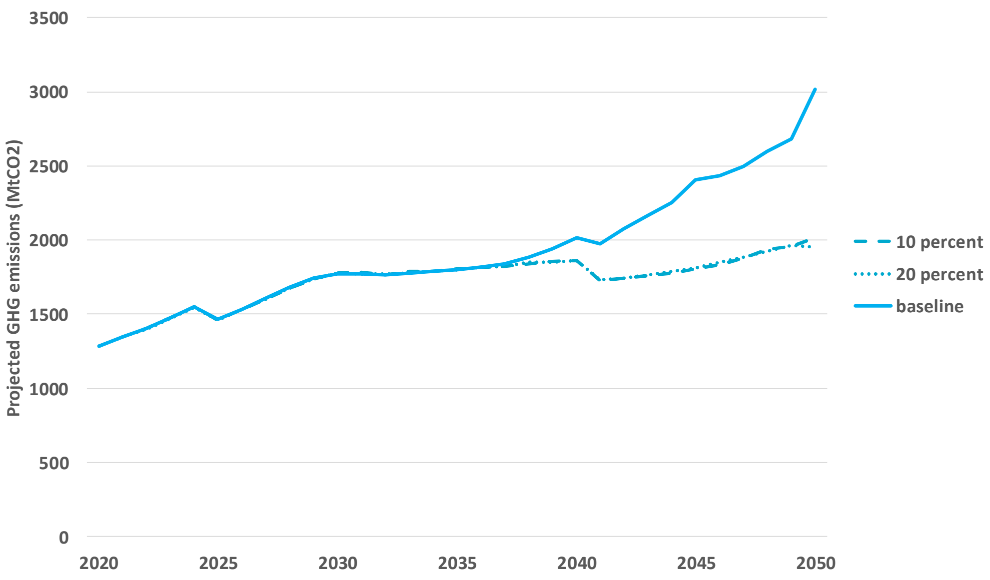

Figure 45 Projected Indian GHG emissions under the 4DS and China scenarios

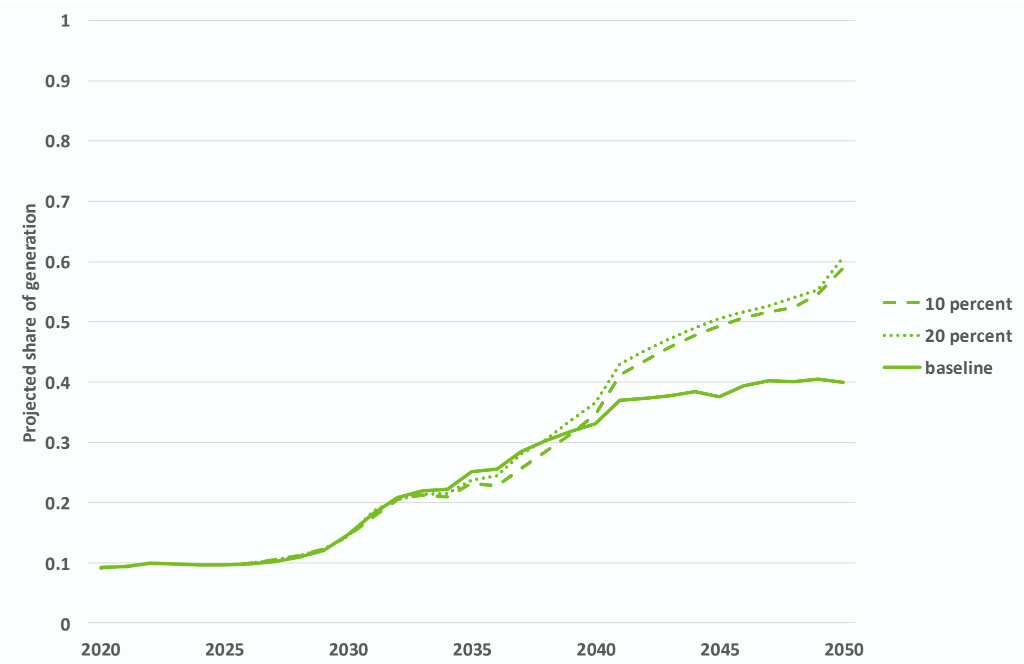

Figure 46 Projected Indian renewable share of generation under the 4DS and China scenarios

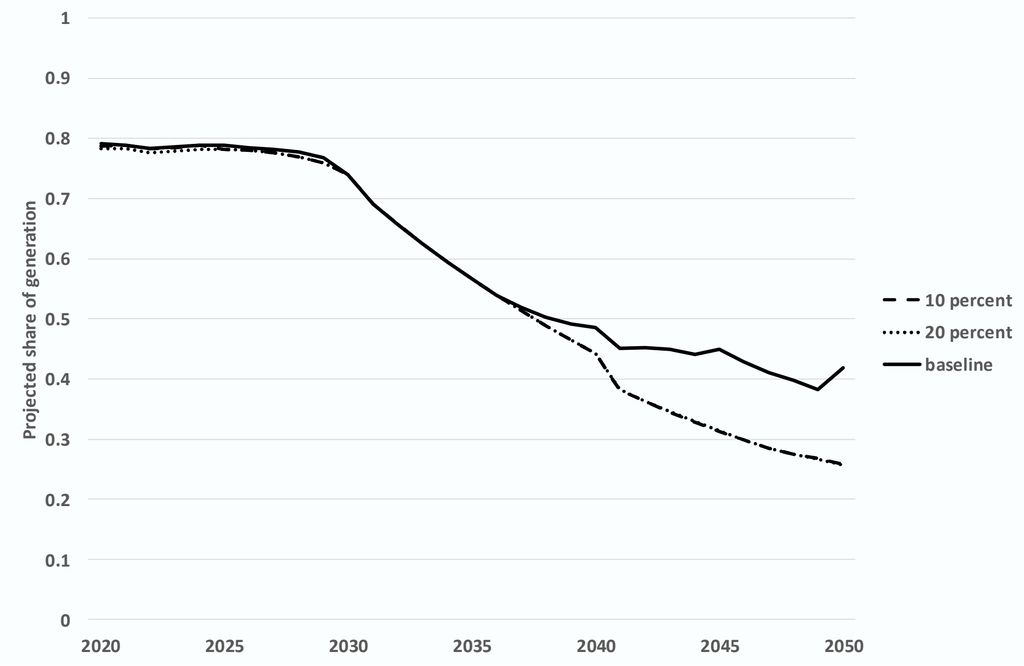

Figure 47 Projected Indian coal share of generation under the 4DS and China scenarios

Under the two gas scenarios, up to 75 GW of offshore wind is built in Europe by 2029 and then an additional 100 GW between 2029 and 2039. This drives the cost of offshore wind down for all regions, making it economic in India. India is a renewable energy-constrained country and needs to rely on higher-cost renewables which are not as constrained, such as offshore wind to decarbonise. It is constrained in land availability and thus CSP is a limited option for India. As a corollary, India builds HELE in the Baseline scenario, because there is CSP in China (and thus elsewhere) resulting in less offshore wind and thus it is uneconomic in India.

SEA

The results for SEA are shown in Figure 48 - Figure 50. The 20% scenario results are indistinguishable, but the 10% results are quite different. The 10% China scenario has lower GHG emissions, more renewables and less coal than the 10% Asian scenario. SEA has relatively low electricity demand and thus its generation mix is heavily influenced by the generation mixes of other regions. India does not build HELE in the 10% Asian scenario, therefore, SEA does not build it either as it is no longer economic. Instead, SEA constructs more renewables such as hydro (36 GW), large-scale solar PV (40 GW), solar thermal (29 GW), offshore wind (35 GW) and gas combined cycle (49 GW).

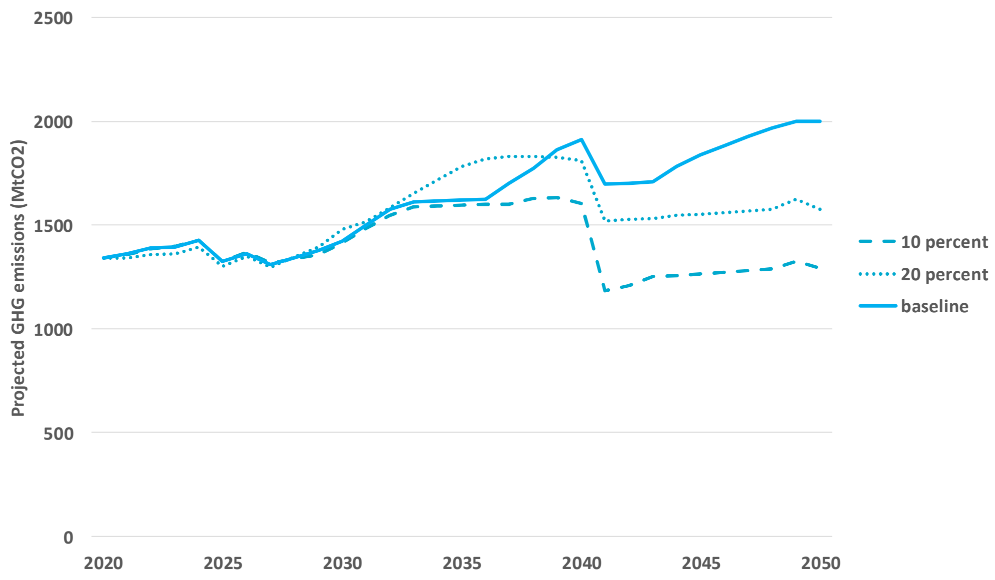

Figure 48 Projected SEA GHG emissions under the 4DS and China scenarios

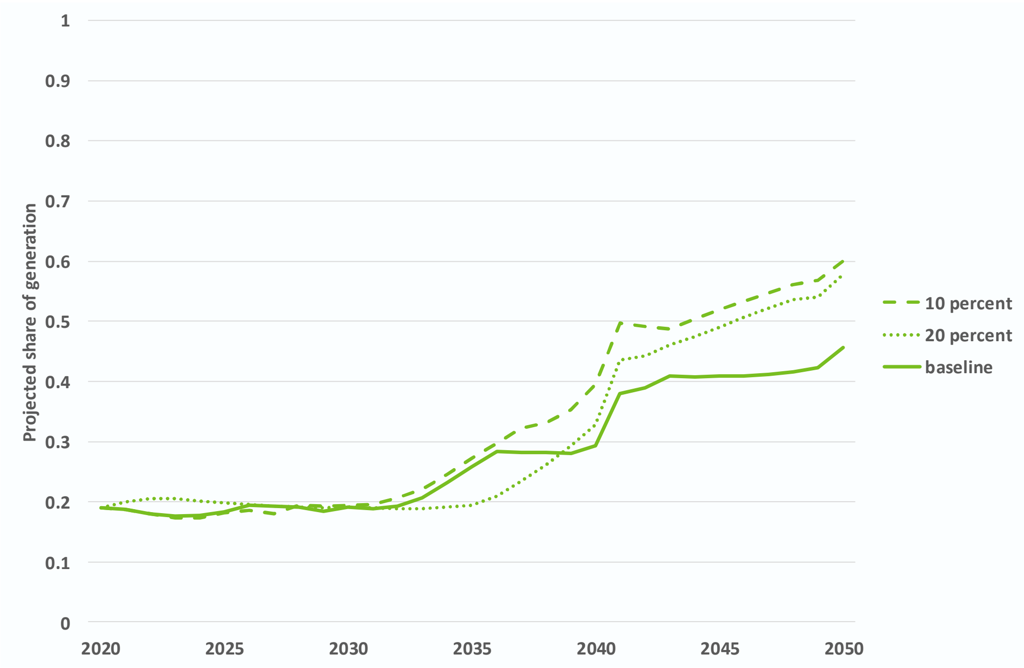

Figure 49 Projected SEA renewable share of generation under the 4DS and China scenarios

Figure 50 Projected SEA coal share of generation under the 4DS and China scenarios

3.3 Summary of climate change impacts

Cumulative global emissions from coal, gas and oil-fired generation have been calculated over the 2020 to 2050 time period and are presented for the SDS-equivalent Asian (Figure 51) and China (Figure 52) scenarios and the 4DS Asian (Figure 53) and China (Figure 54) scenarios. The average grid GHG emissions intensity has also been overlayed, noting that there is no such thing as a global grid, but this metric also includes the contribution of renewable electricity generation and takes into account the differences in total electricity generation (which is higher in the 4DS scenario).

Figure 51 shows that under a high carbon price world and when 10 percent additional gas is available in Asia, coal-fired electricity generation is not impacted and GHG emissions increase overall (from gas). However, when 20 percent additional gas is available in Asia, the cumulative GHG emissions from coal-fired electricity generation are 21% lower than under the Baseline and 10 percent scenarios and the GHG emissions from gas are equivalent. The average cumulative grid GHG emissions intensity is 10% lower than the Baseline, which means that electricity generation from coal is being replaced by renewable electricity generation supported by the additional gas, and there is additional uptake of renewable electricity generation globally.

When additional gas is only made available to China in a high carbon price world, cumulative GHG emissions from coal-fired electricity generation decrease, more so (by 19%) when 10% additional gas is available compared to 20% additional gas (by 7%) as shown in Figure 52. This follows the trends seen in Section 3.1.2 Global results, where 20% additional gas results in a delay in offshore wind and large scale solar PV deployment globally because there is no need to install these technologies in China and China is the country that drives down the cost of these technologies through local deployment.

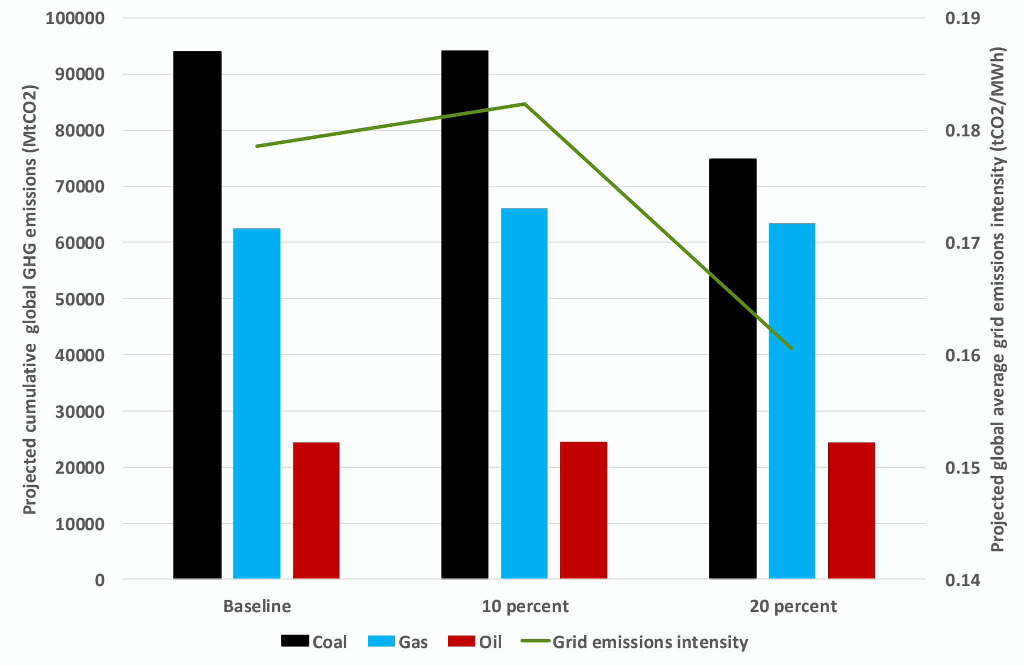

Figure 51 Projected cumulative global GHG emissions and average grid intensity under the SDS-equivalent and Asian scenarios

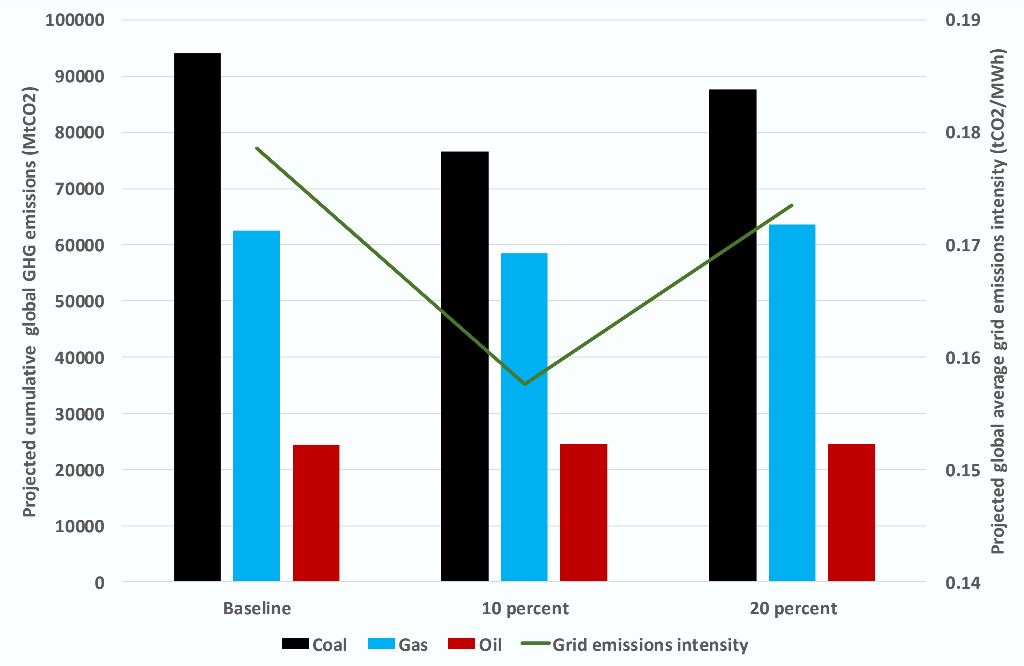

Figure 52 Projected cumulative global GHG emissions and average grid intensity under the SDS-equivalent and China scenarios

Both 4DS scenario figures show much higher cumulative GHG emissions from coal-fired electricity generation and average cumulative GHG emissions grid intensities than the SDS-equivalent scenarios.

Figure 53 shows the results under the Asian scenario and Figure 54 shows the results under the China scenario. Both of these scenarios have similar results. There is only a slight reduction in cumulative GHG emissions from coal-fired electricity generation (by 5%) when 20% additional gas is available for use and the average cumulative grid GHG emissions intensity is around 2% lower than the Baseline. When 10% additional gas is available electricity generation from coal is not impacted, GHG emissions increase and the average grid cumulative GHG emissions intensity increases globally. In these scenarios, the additional gas and renewable electricity generation are replacing some coal-fired electricity generation but not to the same extent as under the SDS-equivalent scenarios.

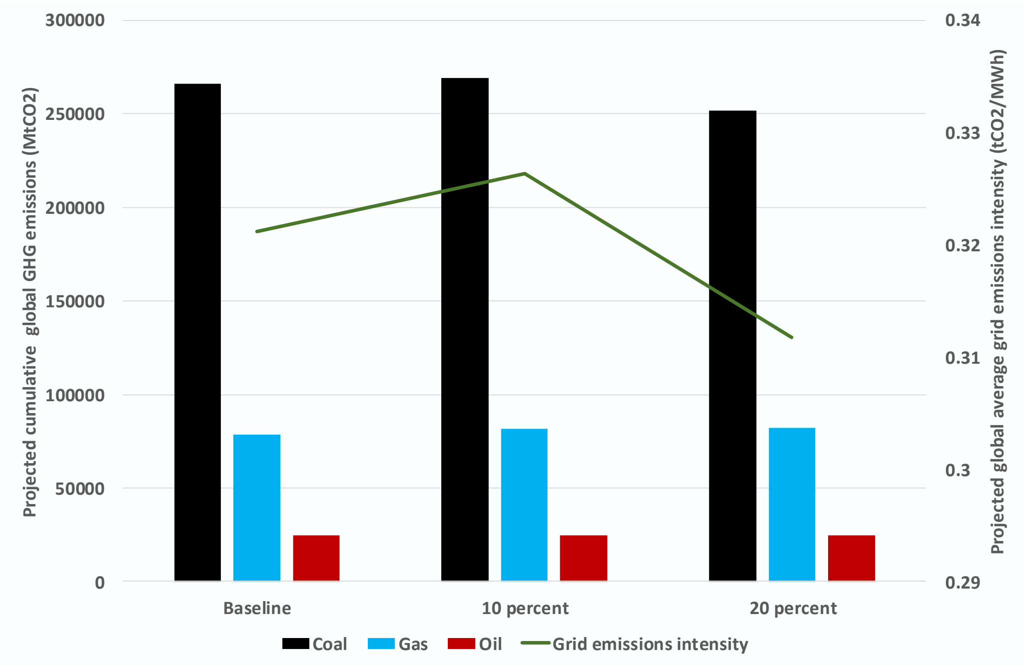

Figure 53 Projected cumulative global GHG emissions and average grid intensity under the 4DS and Asian scenarios

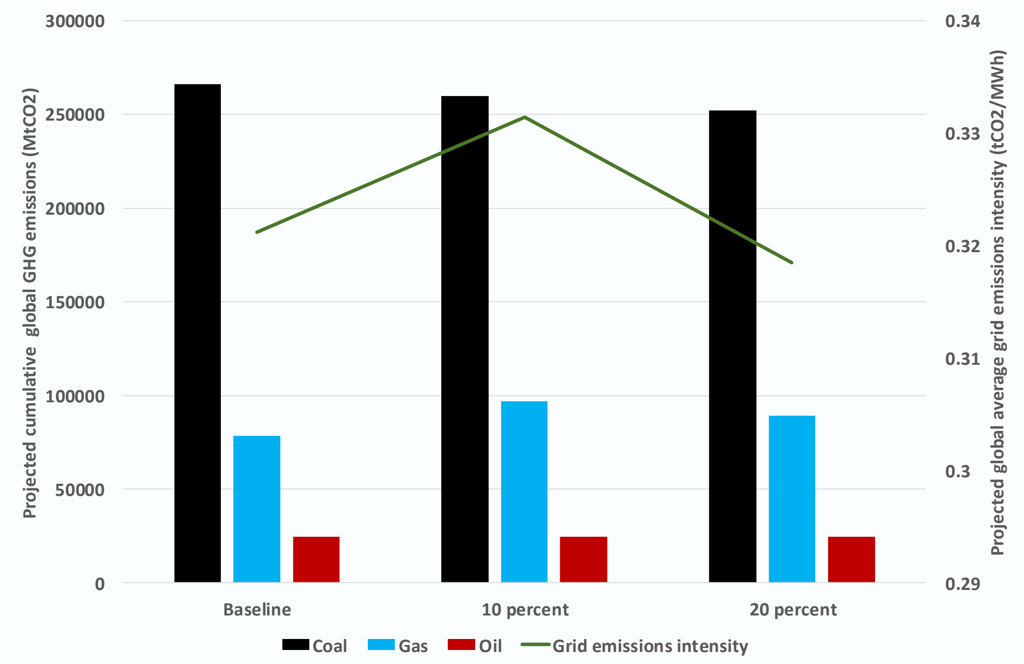

Figure 54 Projected cumulative global GHG emissions and average grid intensity under the 4DS and China scenarios

4 Conclusions

Under the SDS-equivalent scenarios with additional gas (both Asian and China gas supply scenarios) China, India and SEA have strong incentives to decarbonise but dissimilar renewable energy resources. China steadily adopts renewables with a long-term share of 90%. SEA replaces coal-fired power generation with gas-fired power generation and renewables. India tends to opt for gas with CCS to replace coal-fired electricity generation due to limitations on renewable energy resources. However, when only a small amount of additional gas is available (10%), this is not enough to replace coal in all Asian regions (mainly India) and thus GHG emissions increase due to the combined impact of additional coal and gas. When 20% of additional gas is available, coal is forced out earlier, gas supports higher renewable shares faster in regions such as China with unlimited renewable energy resources and increases the deployment of gas with CCS.

Post-2040 the impact of increased gas supply is neutral in the SDS-equivalent scenarios since carbon prices have already forced the major technology transitions to be achieved.

Under the 4DS scenario with additional gas, CCS is not deployed as the carbon price is not high enough to provide sufficient incentive. This means that additional gas is used in gas combined cycle and peaking plants. In China, coal-fired electricity generation remains a primary contributor to electricity generation and the additional gas only increases GHG emissions. In SEA and India, gas replaces new build coal under the 20% scenario and in SEA under both scenarios, but only in the post-2040 period when carbon prices are higher.

In summary, it can be concluded that the results in this report indicate gas remains a transitional fuel but perhaps not precisely in the way it has been previously thought. Gas can assist GHG emissions mitigation during the period when carbon prices or equivalent signals are strong enough to force high renewable electricity generation shares. Until the carbon price reaches that strength, increased gas supply's impact on GHG emissions reduction is either negative or neutral. Also, after renewables have reached a high share, additional gas supply has nothing further to contribute to emission reduction.

China is the main driver behind the global results given its high and growing demand for electricity. As a result, it has a high level of influence, through technology learning-by-doing, over the generation mixes in other regions. China is not renewable energy resource constrained, thus it can build a variety of renewable electricity generation technologies. When it increases its renewable share, it does so as the main early constructer of CSP and through technology learning, it brings the cost of this technology down for all other regions as a global learning effect.

The main impact of this is on other high-cost renewables like offshore wind, which cannot compete with low cost variable renewables and CSP in these scenarios. However, when China does not build much CSP, this technology remains high cost and regions such as Europe construct offshore wind, which brings the cost of this technology down in all regions. India, in particular, benefits from shared learning with Europe on offshore wind as India is renewable energy resource-constrained (due to land availability), and offshore wind is one of its largest renewable energy resources.

Therefore, China influences the uptake of renewable electricity generation technologies in other regions. This is not as evident in unconstrained renewable energy resource regions but is a driver in renewable energy resource-constrained regions like India and SEA.

Appendix A Additional results for Asia

The Asian results are similar to the global results. They have been included in the Appendix for completeness.

A.1 SDS-equivalent scenario

A.1.1 Additional gas in all Asian markets

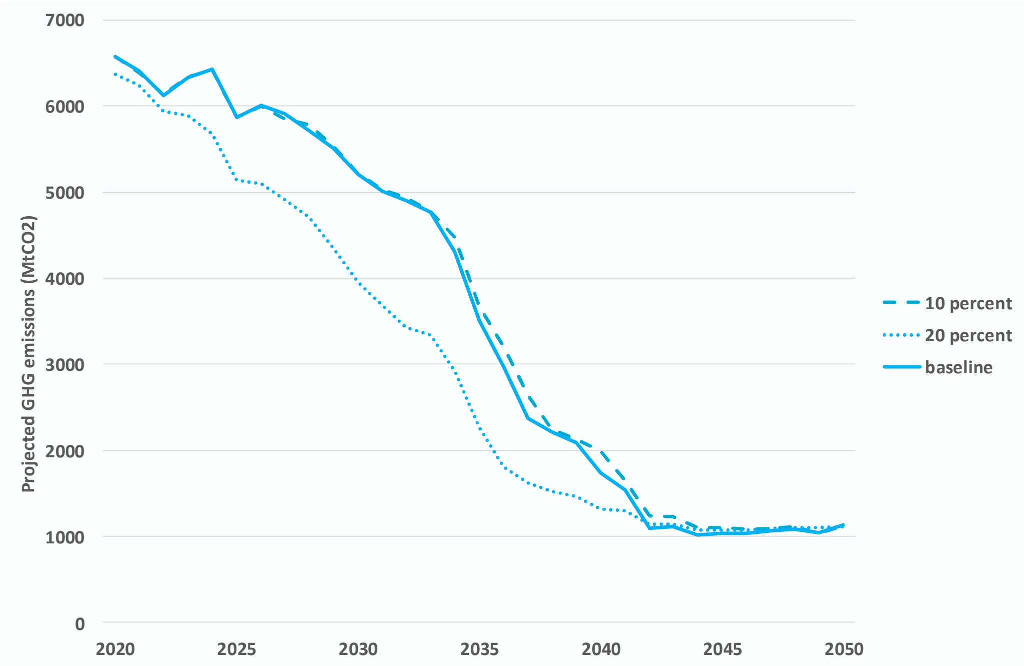

Figure 55 Projected Asian GHG emissions under the SDS-equivalent and Asian scenarios

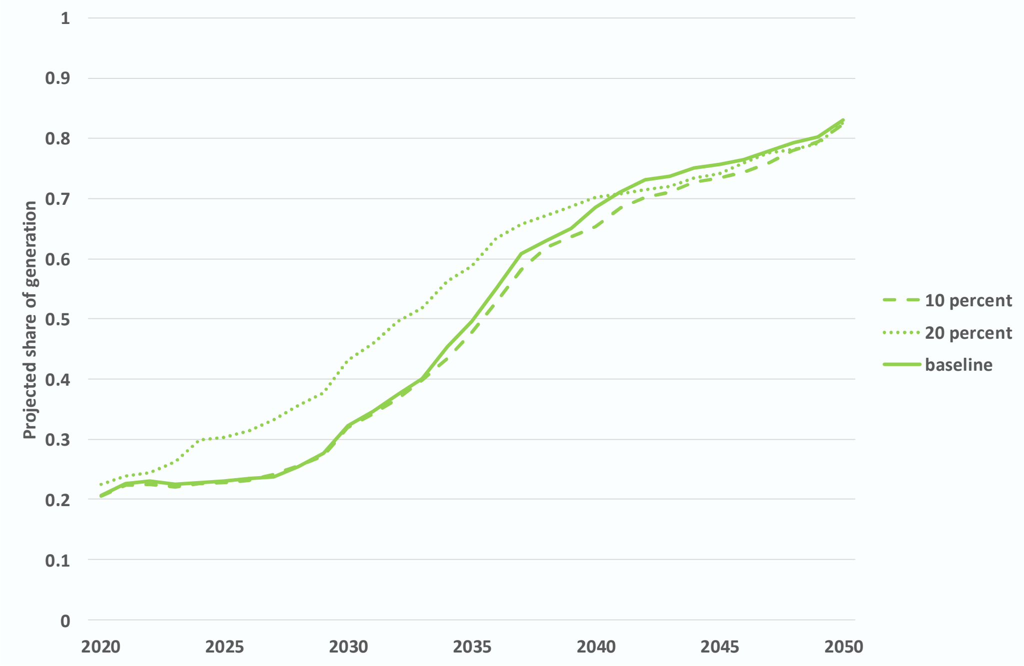

Figure 56 Projected Asian renewable generation share under the SDS-equivalent and Asian scenarios

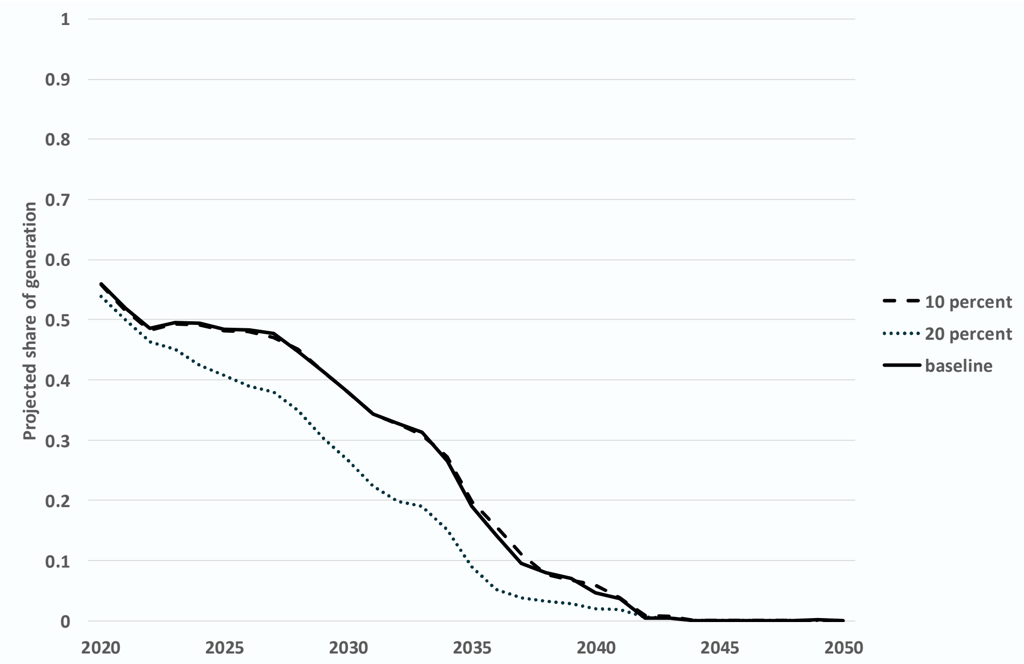

Figure 57 Projected Asian coal generation share under the SDS-equivalent and Asian scenarios

A.1.2 Additional gas in China only

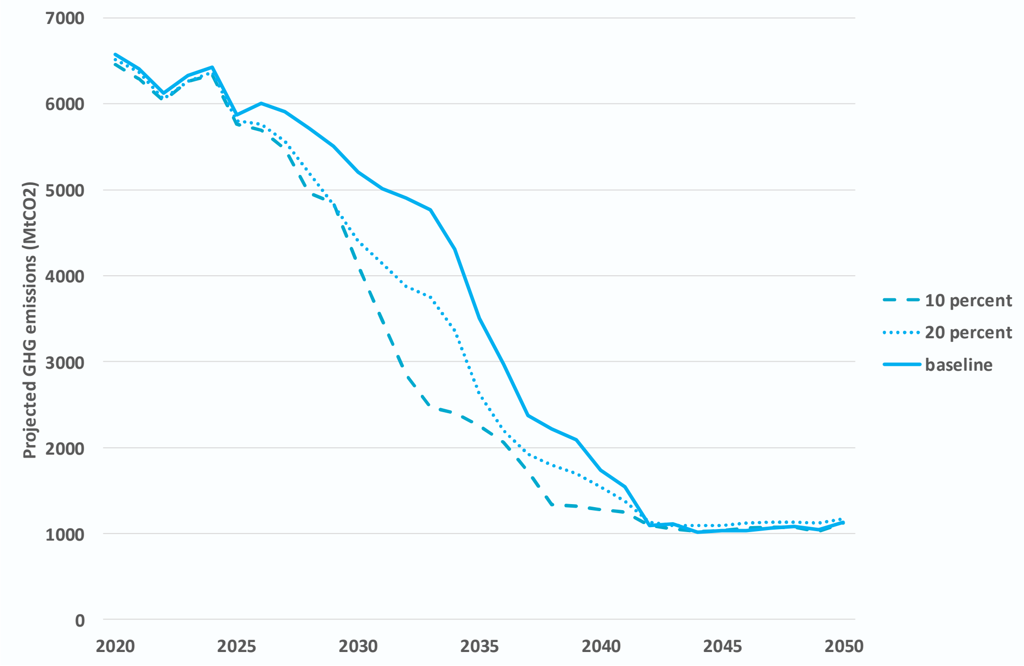

Figure 58 Projected Asian GHG emissions under the SDS-equivalent and China scenarios

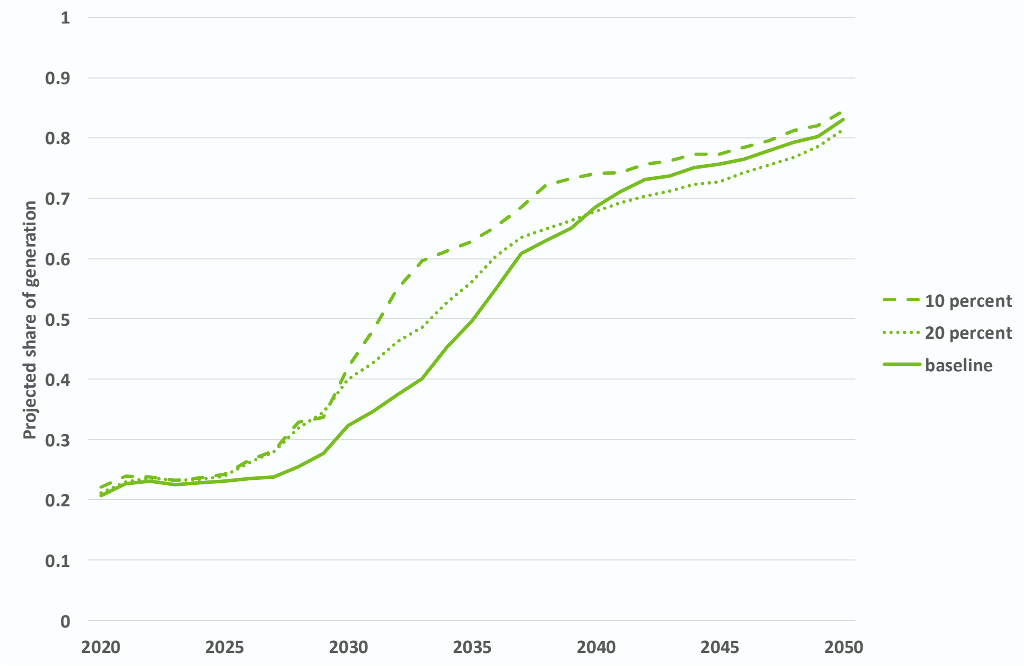

Figure 59 Projected Asian renewable generation share under the SDS-equivalent and China scenarios

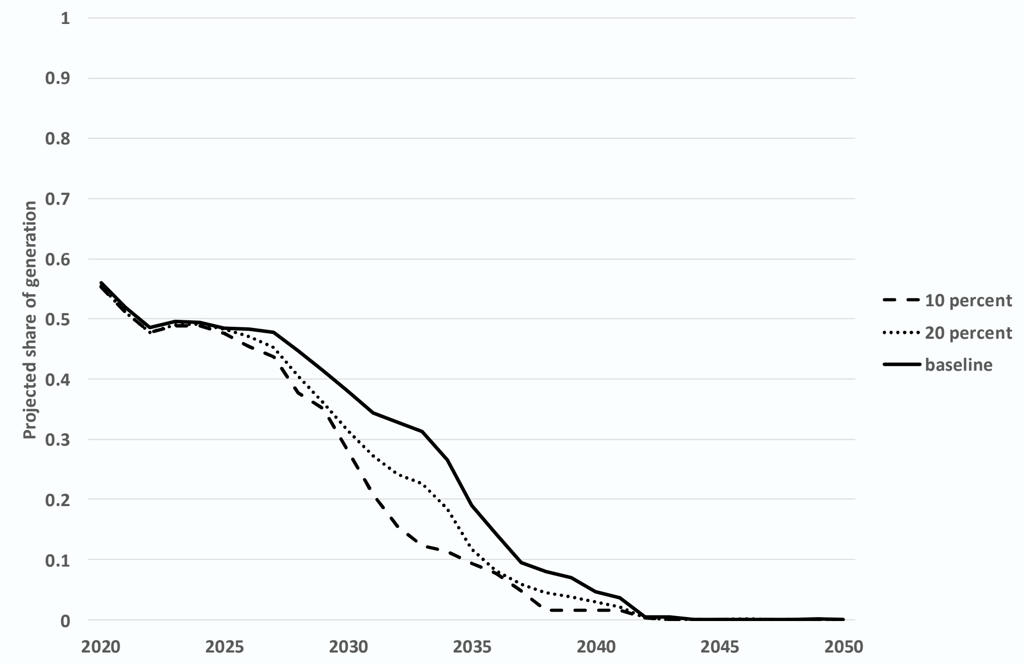

Figure 60 Projected Asian coal generation share under the SDS-equivalent and China scenarios

A.2 4DS scenario

A.2.1 Additional gas in all Asian markets

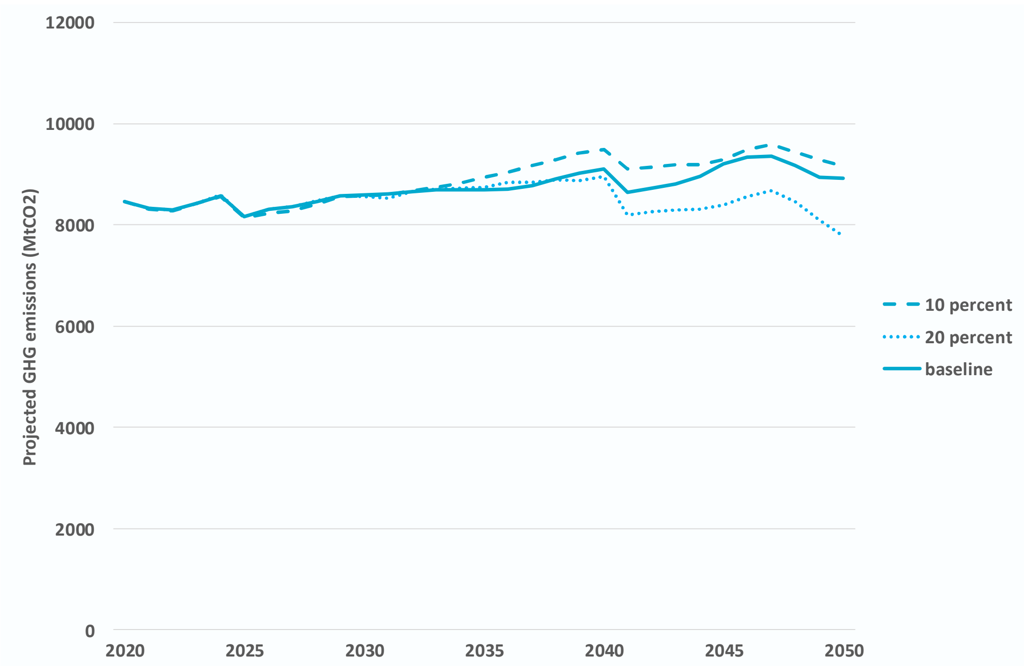

Figure 61 Projected Asian GHG emissions under the 4DS and Asian scenarios

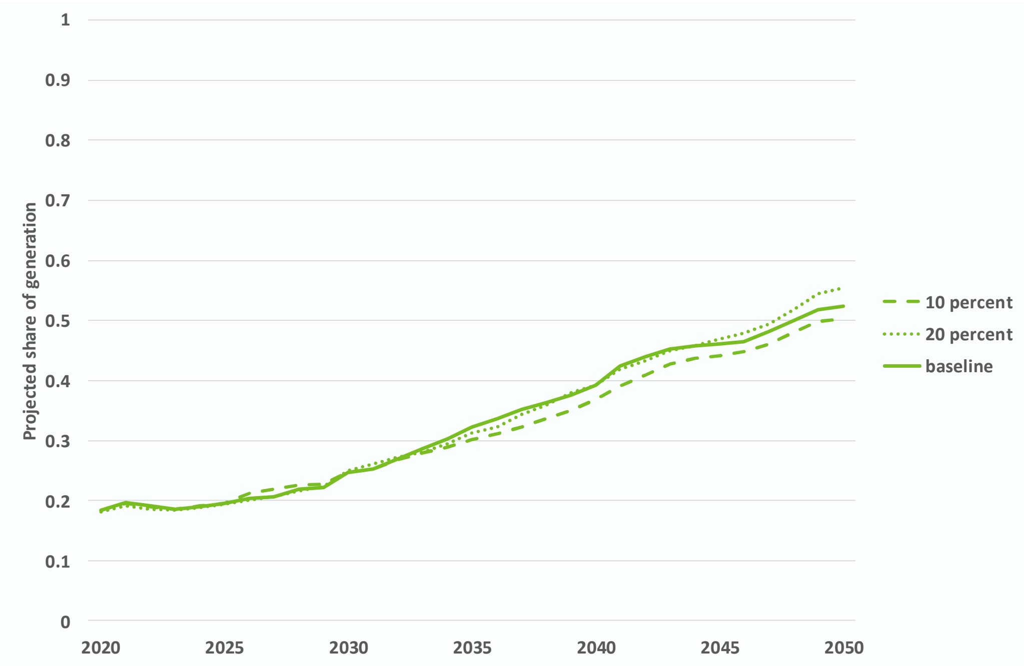

Figure 62 Projected Asian renewable generation share under the 4DS and Asian scenarios

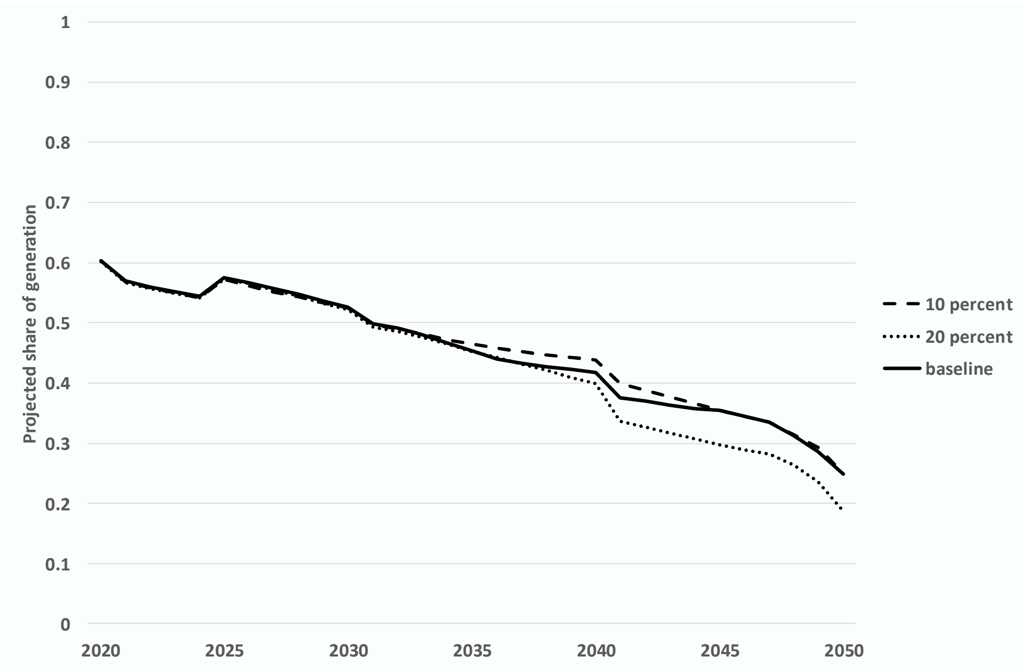

Figure 63 Projected Asian coal generation share under the 4DS and Asian scenarios

A.2.2 Additional gas in China only

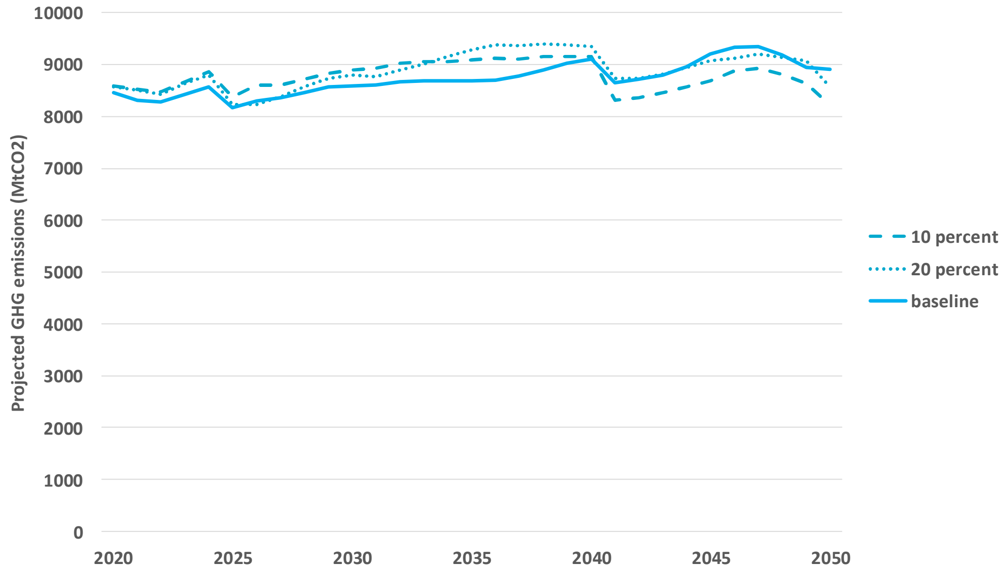

Figure 64 Projected Asian GHG emissions under the 4DS and China scenarios

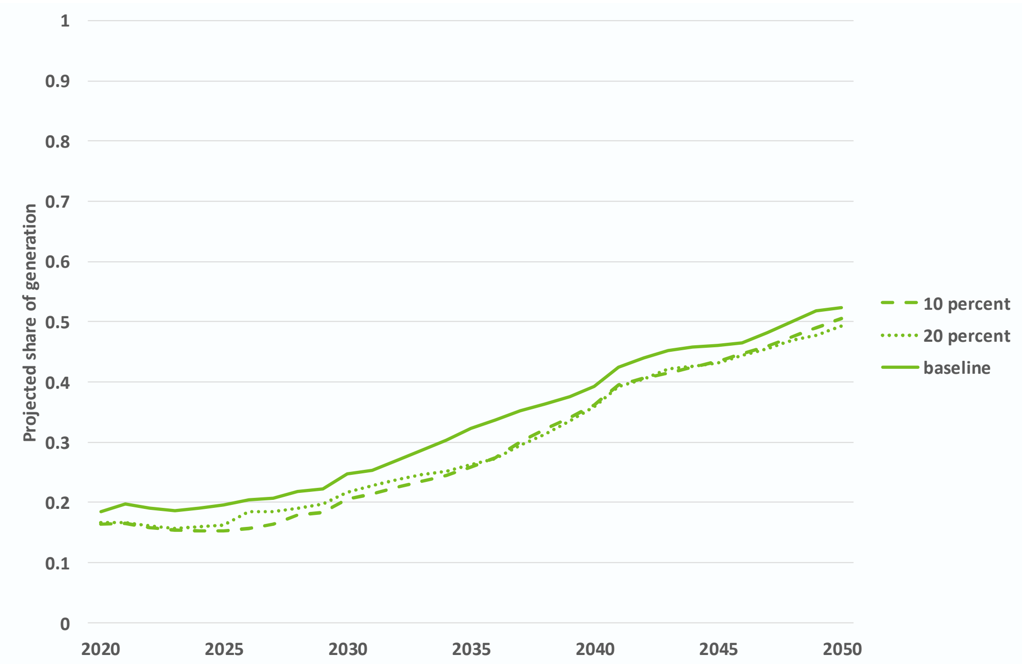

Figure 65 Projected Asian renewable generation share under the 4DS and China scenarios

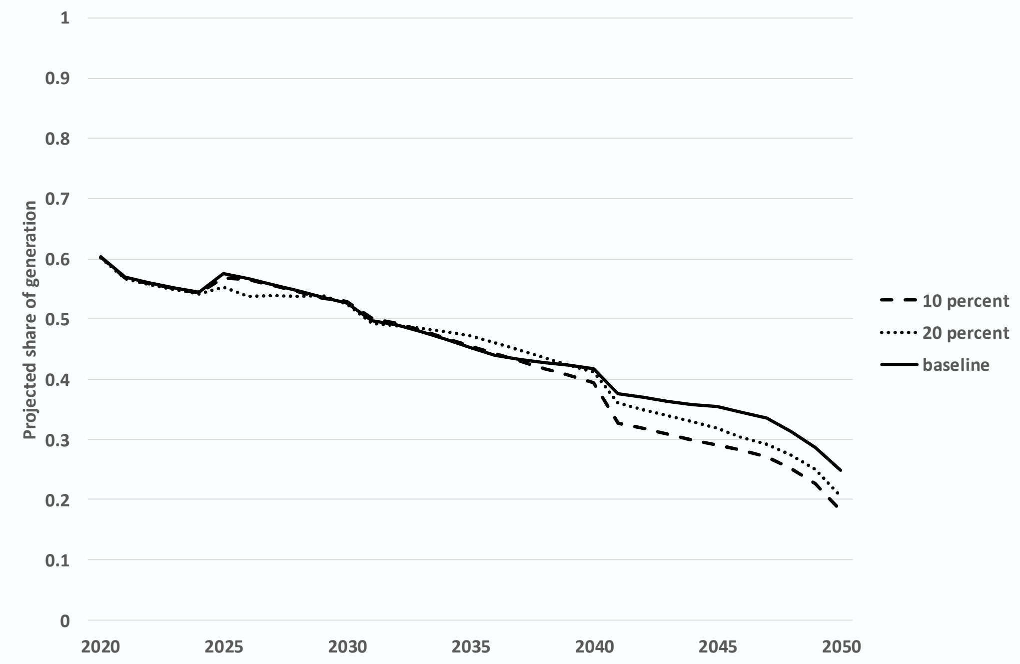

Figure 66 Projected Asian coal generation share under the 4DS and China scenarios

Appendix B Mixed Integer Linear Programming

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GALLM-E is solved as a Mixed Integer Linear Program (MILP).

MILP is a non-linear extension of the more common linear programming (LP) approach to modelling economic relationships such as those involving flows of energy, material and labour. In a LP approach, we can describe the boundaries of our system using lines and planes (and hyperplanes in higher dimensions). Mathematically, we use simultaneous linear equations and inequalities, known collectively as constraints. These constraints relate economic outputs to economic inputs as proportions, scalar multiples and sums. As a result, in LP, any given scenario looks geometrically like a continuous region (an area, volume or hypervolume) with flat edges (left side of Figure 67). We can move from any point within the feasible area to any other point along a line by continuously changing some or all of the variables in the model. We can search for the best choice of variable values in the area by moving along lines and edges to the optimal point.

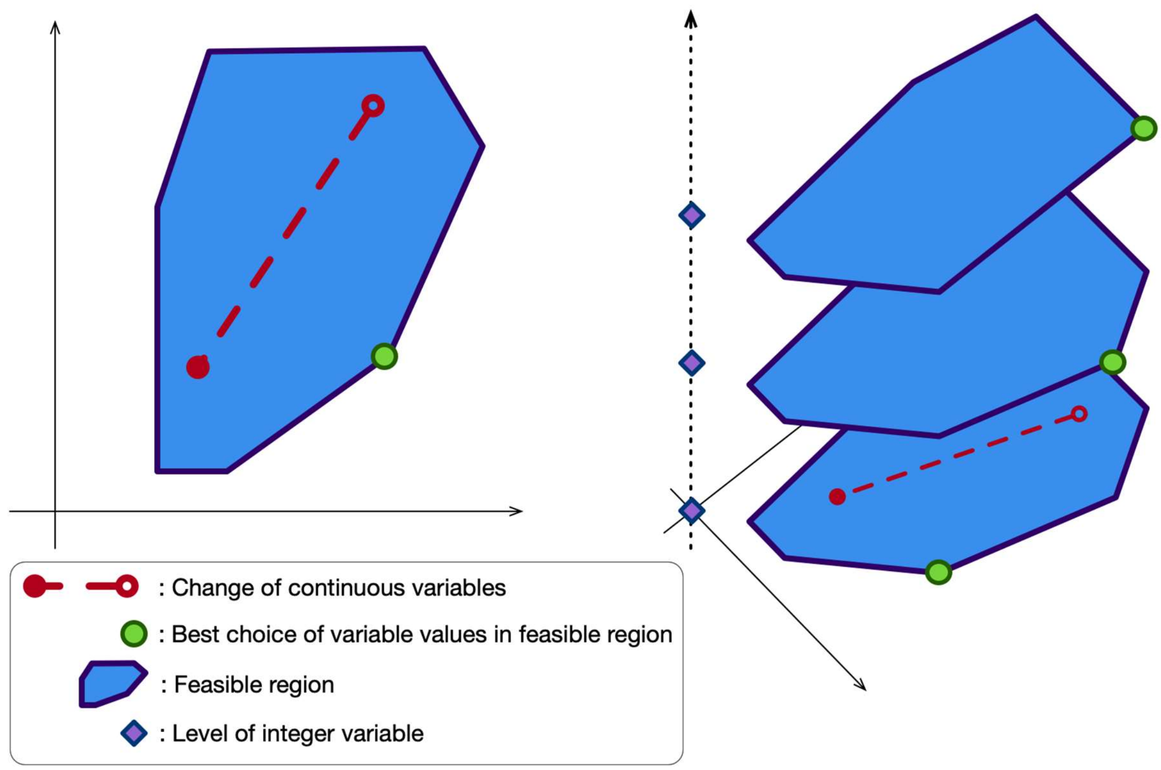

Figure 67 Diagram demonstrating the difference between a feasible region in LP (left) and feasible regions in MILP (right)

The case of a single continuous region in LP is a special case of the more general approach of MILP. We now have a mix of linear constraints expressed using continuous variables and new types of variables. These variables take on a discrete set of integer value (a choice from, for example, just

0, 1, 4 or 10 rather than every real number from 0 to 10). Integer variables may often correspond to on-off switches or mutually-exclusive alternatives that must be accounted for in the model.

The impact on the model when we have a mix of continuous and integer variables is that our scenario's feasible region is now a *collection* of areas (right side of Figure 67). Each separate area corresponds to *fixing* all the model's integer variables at a given combination of values. There is no way to continuously connect a point between feasible regions having *different values* of integer variables. This means the solution algorithm must be more sophisticated by taking into account the switching between disconnected areas before a truly optimal point is found. As a consequence, it also means that small changes in model assumptions may result in obviously different results. This may occur when the optimal point is located in a feasible region with a different set of values of the integer variables.

Shortened forms

ABBREVIATION	MEANING
AUD	Australian dollars
CCS	Carbon Capture and Storage
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide-equivalent
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSP	Concentrating Solar Power
4DS	4-degrees Scenario
GALLM-E	Global and Local Learning Model - Electricity
GHG	Greenhouse gas
GW	Gigawatt
HELE	High Efficiency Low Emissions
IEA	International Energy Agency
LNG	Liquefied Natural Gas
LP	Linear Programming
MILP	Mixed Integer Linear Programming
Mt	Million tonnes
OECD	Organisation for Economic Co-operation and Development
PV	Photovoltaics
SDS	Sustainable Development Scenario
SEA	South East Asia
UN	United Nations

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