CLIMATE ANALYTICS

WESTERN AUSTRALIA'S GAS GAMBLE

Implications of exploiting Canning Basin and other unconventional gas resources for achieving climate targets

Bill Hare, Niklas Roming, Ursula Fuentes Hutfilter, Michiel Schaeffer, Matt Beer

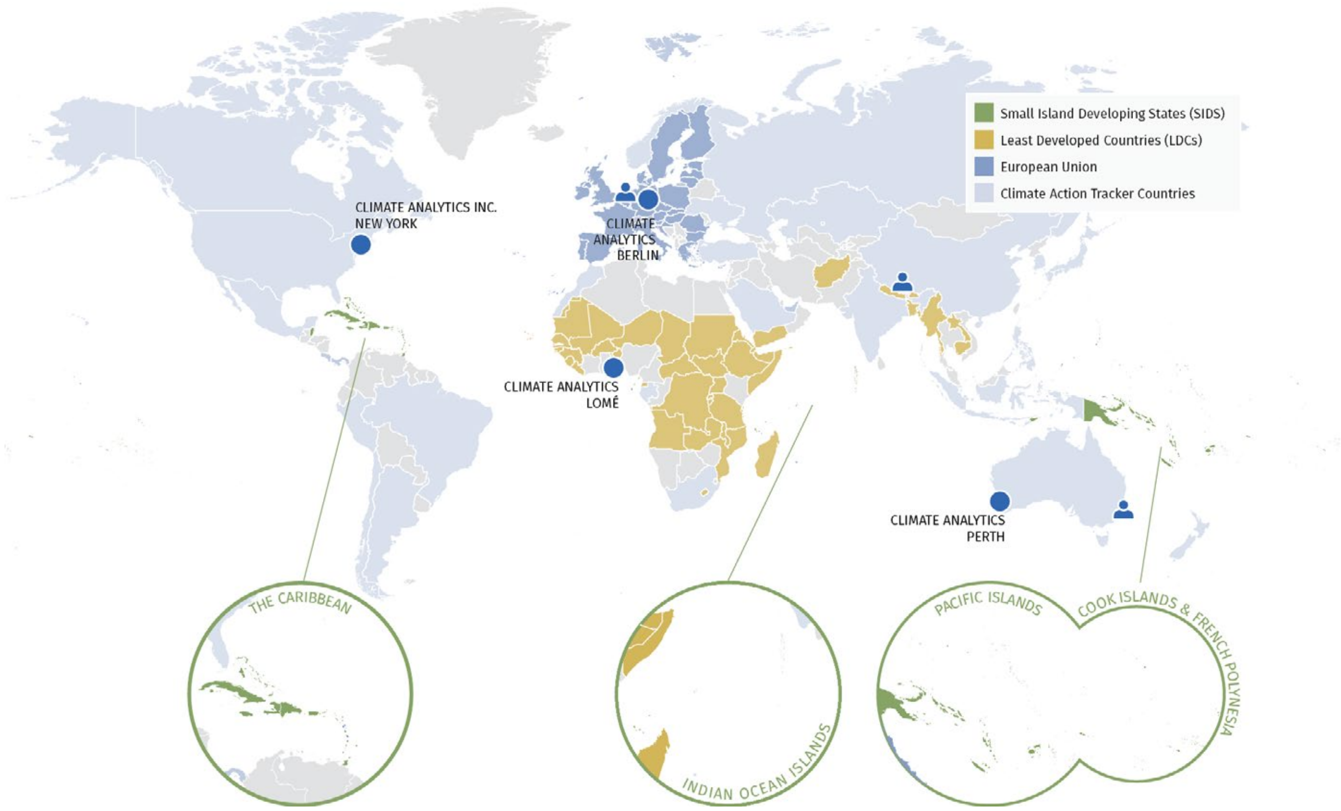
MARCH 2018

WESTERN AUSTRALIA'S GAS GAMBLE

Implications of exploiting Canning Basin and other unconventional gas resources for achieving climate targets

Climate Analytics is a non-profit organisation headquartered in Berlin, Germany, with regional offices in Lomé, Togo, Perth, Australia and New York, USA and with associates across Europe, South America, Asia, Africa, the Pacific and the Caribbean. The organisation's main mission is to synthesise and advance scientific knowledge in the area of climate change. The team is backed by its own and co-developed science-based models to assess and synthesise climate science and policy. By linking scientific and policy analysis, we provide state-of-the-art solutions to global and national challenges posed by climate change.

Through its unique position at the interface between science, policy and practice, and with its excellent international networks, Climate Analytics has established itself as a strategic knowledge partner for key matters concerning climate research and policy.



Dr Bill Hare
Director, Climate Analytics
Adjunct Professor, Murdoch University
School of Engineering, Perth Western Australia

Contact details
E-mail: bill.hare@climateanalytics.org
Phone: +61 468 372 179
web www.climateanalytics.org

EXECUTIVE SUMMARY

With its vast reserves, Western Australia is a global player when it comes to natural gas. By the end of 2018, its liquefied natural gas (LNG) production will account for around 11% of global capacity. Any decision Western Australia makes when it comes to new gas projects will have a global impact. By the same token, how the global energy markets respond to the global shift away from fossil fuels and towards renewable energy will have serious implications for the profitability of current and potential natural gas projects in Western Australia.

At present these developments focus on conventional natural gas resources but now the development of unconventional resources, including exploiting shale gas in the Canning Basin using hydraulic fracturing (fracking) is under discussion. In addition to environmental impacts associated with fracking, these resources contain much more energy and carbon than conventional resources and using them would entail large carbon emissions. Additionally, because shale gas and other unconventional resources are so much more difficult to extract, they also have a substantially higher risk of leakage and losses of methane – a powerful greenhouse gas released during the extraction process.

As a Paris Agreement signatory, Australia - and thus by extension Western Australia - need to reduce their greenhouse gas emissions to be in line with the climate treaty's long-term objective to hold global temperature rise to "well below" 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C. The world has warmed by 1°C since the Industrial Revolution and even at this level of warming Australia is already experiencing severe climate impacts – from coral reef loss to devastating bushfires linked to increasingly long and intense heat waves and droughts. Limiting warming to 1.5°C is particularly important to Australia as it represents a chance to avoid much worse climate impacts.

To keep the chance to limit dangerous climate change within reach and meet the goals set out in the Paris Agreement, there's a limited amount of carbon the world can emit collectively – the so-called global carbon budget. Australia's share of this carbon budget – and Western Australia's portion of it – is correspondingly limited. The global carbon budget is shrinking rapidly even without any new fossil fuel developments. We show in this report that any new gas development in Western Australia based on unconventional resources – globally significant by their sheer scale – would undermine both Australia's and the world's efforts to meet the Paris Agreement's climate goals.

By signing the Paris climate agreement, governments, including Australia, agreed that greenhouse gas emissions must reach zero globally within the second half of this century, which spells trouble also for the natural gas market, as demand is likely to peak within the next ten to fifteen years. As the world begins to implement the Paris Agreement, governments are stepping up efforts to cut emissions and roll out renewable energy. The combination of rapid progress in renewable energy and storage technologies and the continually falling costs, which is making renewables more cost-effective than fossil fuels, including natural gas, in a growing number of markets also casts doubt on the wisdom of developing new gas projects in Western Australia.

At the same time, Western Australia is uniquely placed to take advantage of the economic opportunity the Paris Agreement represents as the world transitions to a low-carbon future. Not only is it rich in minerals needed to make the global low carbon transformation possible but it also has enormous and easily accessible solar, wind and geothermal renewable energy resources.

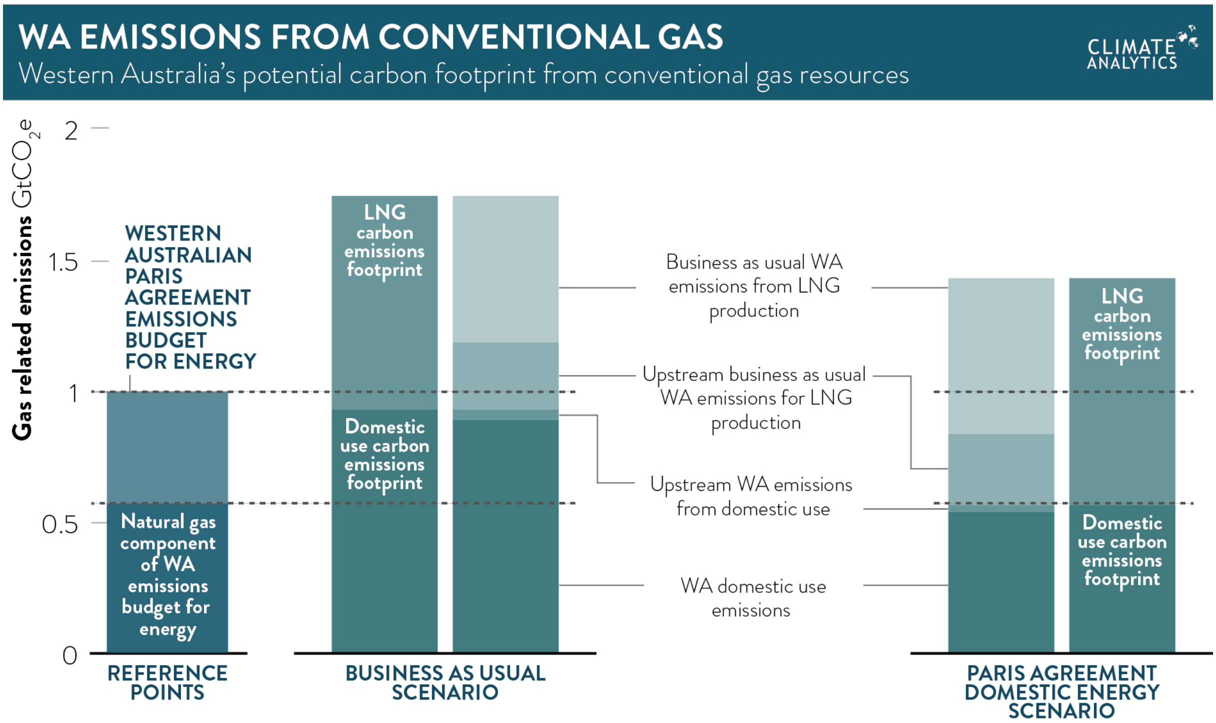
This report does two things. Firstly, it shows how significant the impact of exploiting Western Australia's gas resources would be on achieving state, national and global climate goals. It estimates the carbon footprint of Western Australia's natural gas resources and compares it against the relevant Paris Agreement-compatible carbon budgets – what the world can emit collectively, and what share of it falls to Australia and Western Australia.

Secondly, it looks at how Western Australia could make use of its vast renewable energy potential to transition from a natural gas giant to a renewable energy superpower.

Here are the report's key findings.

DOMESTIC CARBON FOOTPRINT

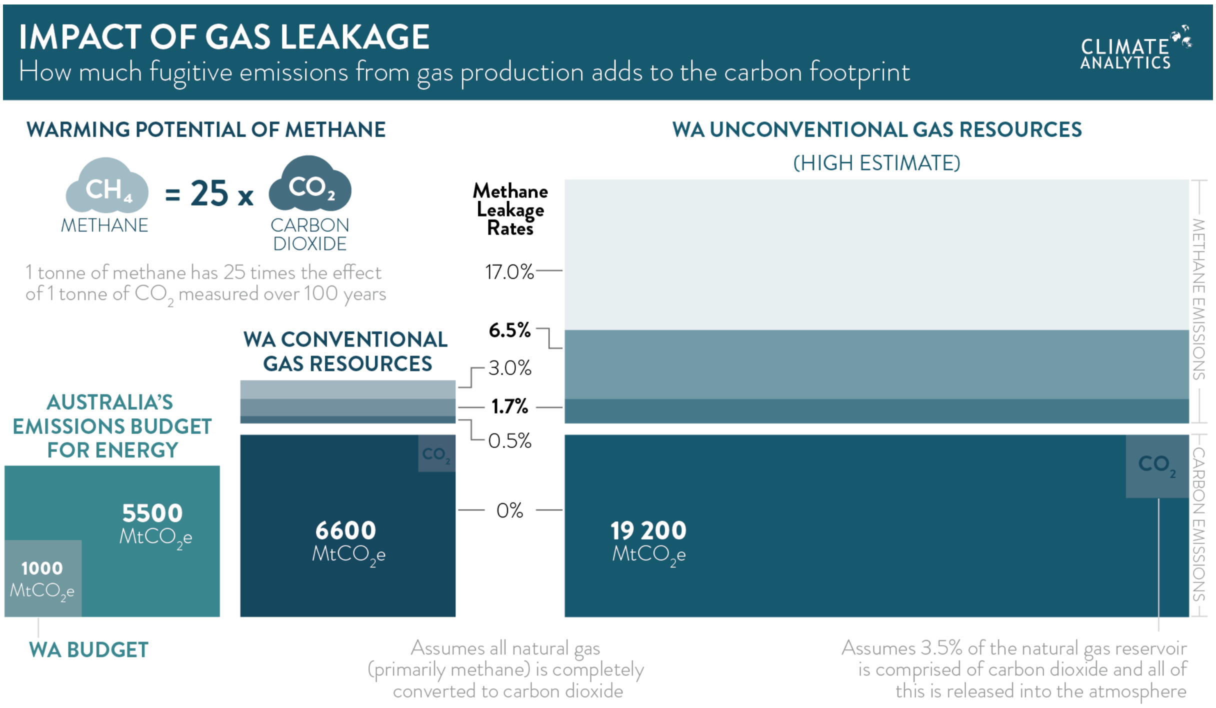
- **The domestic emissions from full exploitation of Western Australia's conventional gas reserves for both domestic use and LNG exports present major challenges for the State to comply with a Paris Agreement-compatible carbon budget**.
- **Under the Paris Agreement, Western Australia will need to move from gas to renewable energy sources by 2050 for its domestic energy needs and as well make very large emission reductions in all phases of LNG production and processing.**



Scenarios for complete use of conventional gas reserves and resources for domestic WA use (business as usual or a Paris Agreement scenario) with remainder of gas resource not used domestically exported as LNG. Carbon footprint compared to WA Paris Agreement compatible energy emissions budget and with the natural gas component of this budget. The Paris Agreement domestic energy scenario shows the carbon footprint for a phase out of domestic gas use in WA by 2050, however the LNG footprint remains high so that the overall emissions far exceed the total emissions budget for the WA energy system. This points to the need for emissions related to LNG production to be reduced very substantially.

- **The domestic emissions expected from all conventional gas reserves are about 40-75% above what Western Australia's energy sector could emit in order to comply with the Paris Agreement.**

- Upstream emissions from domestic use of natural gas - including fugitive emissions during extraction, processing, handling and transportation - would be about 300 million tonnes of CO_2 equivalent (0.30 $GtCO_2e$).
- Emissions from direct use in WA – power production, mineral processing and LNG production add approximately 1.4 billion tonnes of CO_2 equivalent (1.4 $GtCO_2e$)
- Total domestic carbon footprint of conventional gas reserves is about 1.8 billion tonnes of CO_2 equivalent emissions (1.8 $GtCO_2e$). This is about 800 million tonnes above the Paris Agreement-compatible emissions budget for Western Australia, which is one billion tonnes of CO_2 equivalent (1 $GtCO_2e$). This budget is for the whole energy sector including power, industry, transport and buildings, not just those parts that depend on natural gas.

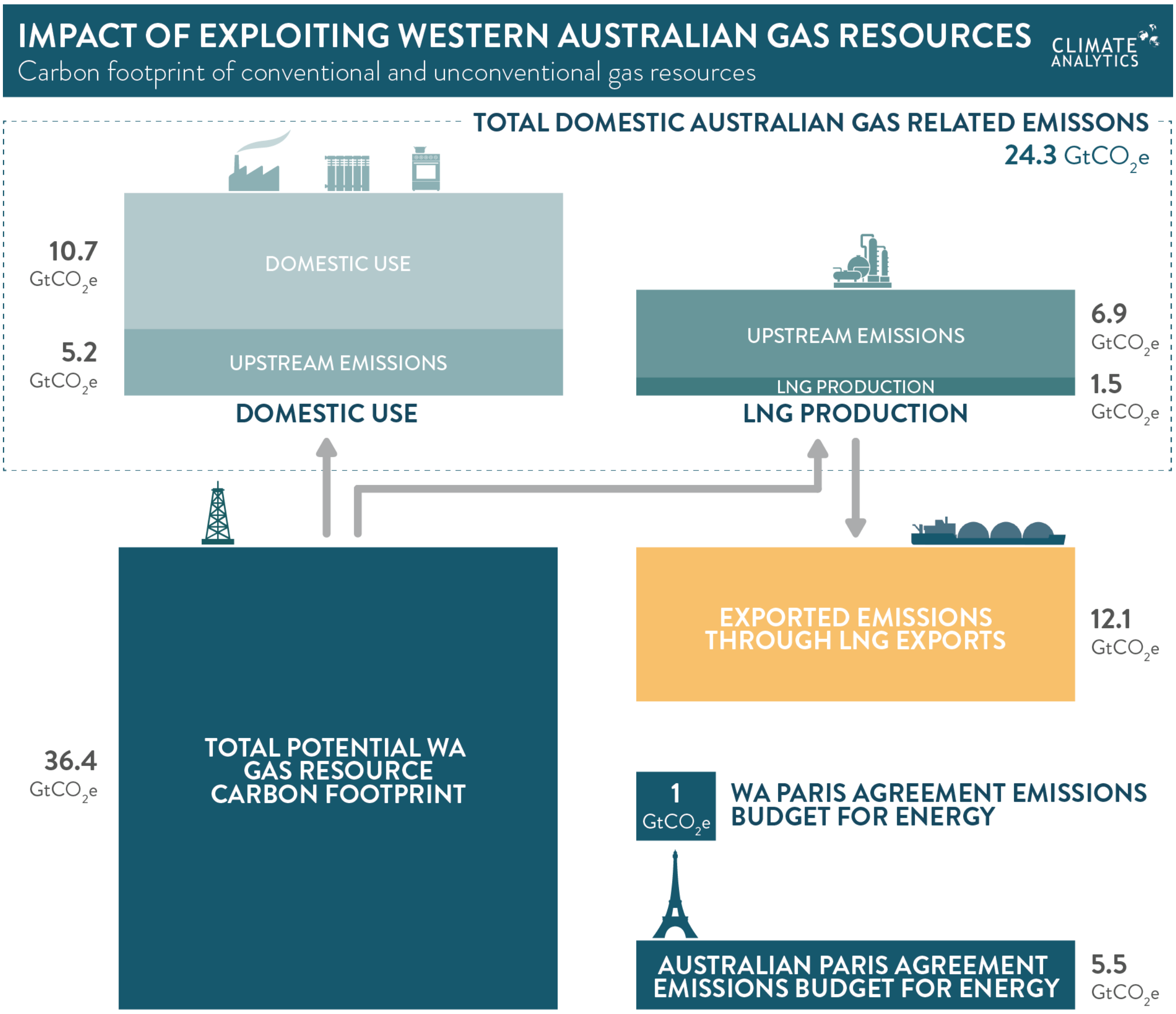


- **The domestic carbon footprint from Western Australia's <u>unconventional gas resources</u> is about three times what Australia is allowed to emit in order to comply with the Paris Agreement. The carbon footprint of Canning Basin resources alone is equivalent to about double this budget.**

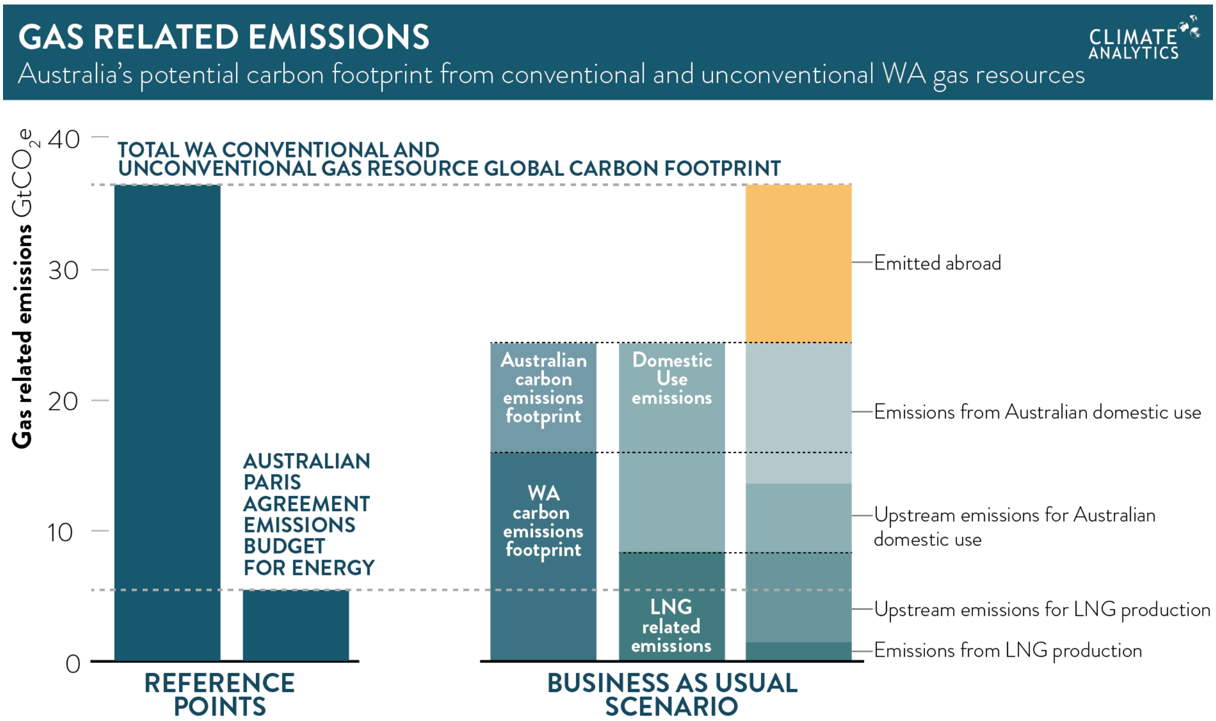
  - Upstream emissions from domestic use of all unconventional resources - including fugitive emissions, extraction, processing, handling and transportation - would between 8 and 12 billion tonnes of CO_2 equivalent (8-12 $GtCO_2e$), and all would likely come from Western Australia.
  - Emissions from direct domestic use of gas and LNG processing add 6-7 billion tonnes of CO_2 equivalent (6-7 $GtCO_2e$), with the majority of these emissions occurring in Western Australia.
  - The total upstream and direct emissions from use of all unconventional resources is about three times Australia's estimated emissions budget under the Paris Agreement, which is 5-6 billion tonnes of CO_2 equivalent (5.5 $GtCO_2$).

- **The domestic carbon footprint from <u>unconventional gas resources</u> would fundamentally undermine Western Australia and Australia's contribution to global efforts to limit warming to 1.5°C.**

- **Canning Basin and other unconventional gas resources are not needed in Western Australia or Australia for the energy transformation required to meet Paris Agreement goals.**
    - While gas will likely play a role in the transition phase towards a zero-CO_2 emissions (e.g. 100% renewable) energy system, Australia and Western Australia's gas demand in this transition can easily be met without any need for WA's unconventional gas resources.
    - In a Paris Agreement-compatible energy transition gas consumption would start declining in the 2020s and reach zero by 2050, with all gas use replaced by renewable energy alternatives.



This shows the carbon footprint for one scenario for complete use of conventional and the present high estimate of unconventional WA gas resource with substantial domestic use (43%) and the remainder use for LNG processing and export.



GLOBAL CARBON FOOTPRINT

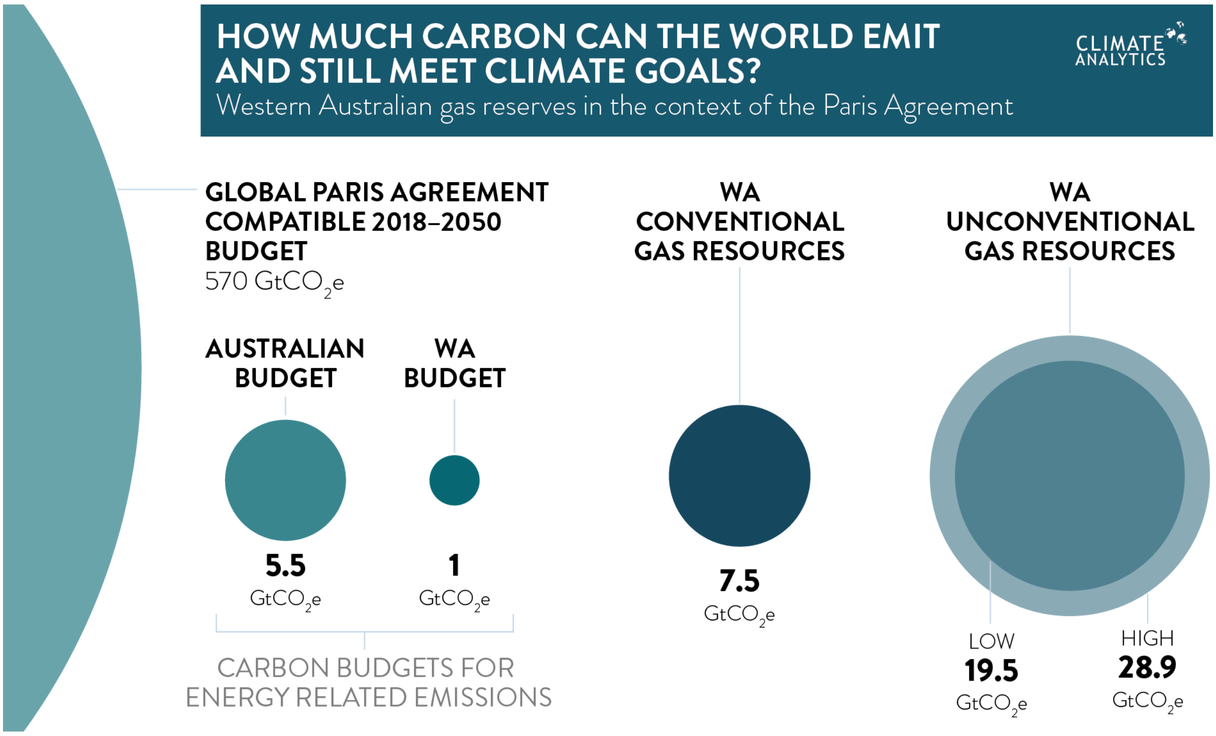
- **The carbon footprint of Western Australia's total gas reserves is globally significant and is equivalent to 4.7%-6.4% of the global energy system carbon budget under the Paris Agreement.**
    - Western Australia's conventional gas reserves have a carbon footprint equivalent to about 1.3% of the global carbon budget under the Paris Agreement.
    - Unconventional gas has a carbon footprint equivalent to about 3.4.% -5.1%[1] of the Paris Agreement-compatible carbon budget for until 2050.
    - The carbon footprint of Canning Basin resources alone is equivalent to about 2.3%-3.6% of a Paris Agreement-compatible global carbon budget. This is much higher than Australia's share of present global energy-related CO_2 emissions (about 1%).

- **The world does not need Canning Basin nor other unconventional gas to transition to a zero-emissions energy system.**
    - The global gas market does not need the additional resources from the proposed development of Canning Basin and other unconventional gas in Western Australia.
    - Global proven gas reserves are already sufficient to meet the demand under Paris Agreement-compatible energy and emission pathways. In fact, less than half of these reserves can be used by 2050 to stay within the Paris Agreement carbon budget.

[1] Assuming leakage rate of 6.5% for unconventional resource development. Lower end of range: lower resource estimate. Higher end of range: Higher resource estimate. Full range for 1.7% loss to highest loss rate of 17% is 2.6%-7.8%

- **Investing in unconventional gas production and transport infrastructure risks a lock-in of carbon-intensive energy mix and stranded assets.**
    - Gas demand will likely peak and decline within 10-15 years as the world implements the Paris Agreement.
    - Present real economy technology trends indicate it is unlikely that gas with Carbon Capture and Storage (CCS) will be deployed at scale in power systems as renewable energy becomes cheaper and more flexible.
    - Exploitation of Canning Basin and other unconventional gas resources in Western Australia is likely lead to large stranded assets, either through investments in pipelines within Australia or LNG export facilities.

In the context of a slump in gas demand expected as the world implements the Paris Agreement, and with extraction and transport costs likely be in the upper end of the global supply cost curve, the profitability of exploiting the Canning gas resources is in doubt.



GLOBAL ENERGY TRANSITION AS AN OPPORTUNITY FOR WESTERN AUSTRALIA

- **Western Australia has an unusually large and accessible combination of renewable resources, notably solar, wind and geothermal, as well as mineral resources critical to the global low-carbon transformation.**

- **Western Australia will need to play its role in reducing greenhouse gas emissions over the next several decades**, within the context and framework of Australia's evolving policy settings. While its energy intensive sector will be a relevant and important consideration in how fast greenhouse gas emissions need to be reduced compared to the national average, ultimately all CO_2 emissions from fossil fuel use will need to be reduced to zero over the next three to four decades. The present lack of a coherent federal policy framework to meet Australia's commitments under the Paris Agreement does not exempt Western Australia from considering the greenhouse gas emissions that would result from specific industrial development proposals. Almost all of Australia's States and Territories have set goals to achieve net zero emissions by 2050. The only exceptions are Western Australia and the Northern Territory.

Many large **companies** active in Western Australia in the energy and resources sector are already actively exploring transition possibilities for their enterprises to significantly reduce CO_2 and other greenhouse gas emissions, while building and maintaining their core business.

- **The global market opportunity for zero carbon energy created by the Paris Agreement presents an unprecedented opportunity for Western Australia to make an orderly and economically beneficial transition from a leading LNG exporter to a global renewable energy superpower.**

- **Western Australia has a natural comparative advantage in terms vast renewable resources, high level technical and engineering capabilities, infrastructure and proximity to Asian energy markets to develop a carbon free energy system for domestic use and exports of renewable energy (electricity or energy carriers such as 'Green' hydrogen) to take the place of LNG and other high carbon energy carriers in international markets.**

Cover photo: Oil & gas drilling pads dotting the landscape of Wyoming, USA. A potential future for WA? © EcoFlight

TECHNICAL SUMMARY

This report addresses the question whether Australia and the rest of the world can meet the Paris Agreement climate goals if Western Australia were to go ahead with the extraction and subsequent use (domestic and/or export) of its vast natural gas resources, in particular the Canning Basin.

Emissions from development of unconventional natural gas resources are globally relevant. This work shows that the greenhouse gas emissions arising from development of unconventional natural gas resources in Western Australia, of which the Canning Basin is the largest part, are globally relevant, and that their development is not consistent with the Paris Agreement goals.

Australia's emissions are increasing. Actual policies are not even sufficient to meet Australia's inadequate Paris Agreement targets for 2030. On current projections, Australia's emissions (excluding land use and land-use change) would increase 8-16% over 2005 levels by 2030. The rapid expansion of LNG processing is a major factor in the emissions increase over the last three years, with further growth in the LNG sector expected as new plants come online in 2018, mainly in Western Australia. Drawing from conventional gas reserves, LNG production is expected to grow nearly 200% between 2015 and 2020, which would lead to an 85% increase in direct combustion emissions from the energy sector in those five years, most of it in Western Australia.

Western Australia's emissions are rising rapidly due to the ramping up of LNG production and export, drawing on conventional gas resources. Emissions related to WA LNG production and processing were about 11 $MtCO_2e$ in 2015 (about 1.9% of national GHG emissions in 2005) and are projected to increase two and a half times by the early 2020s (about 5% of 2005 national GHG emissions), as new LNG plants ramp up to full production.

This creates a significant future mitigation challenge for the state to get onto an emissions and economic development pathway that is compatible with the Paris Agreement. Adding very large emissions from unconventional gas resource exploitation in the Canning Basin could make this challenge impossible. There is an urgent need for Western Australia to develop a strategy to account of the Paris Agreement and the need to reduce CO_2 emissions to zero by around 2050.

WA consumes more gas than any other state in Australia: in 2015-16, WA's domestic gas consumption was 562 Petajoules (PJ), accounting for around 37% of Australia's total gas consumption. Large industrial consumers account for two-thirds of gas used in WA, with 32% used in mineral processing (e.g. alumina, nickel, lithium), 29% in electricity generation, and 23% in the mining sector. About 3% is used in the residential sector. At present LNG processing accounts for about 30% of domestic gas use and is projected to rise to 40-45% by the mid 2020s.

Over 90%, or 113,786 PJ[2], of Australia's total estimated conventional gas reserves and resources[3] are located onshore and offshore in WA (AEMO 2017). In addition, an estimated 222,057-330,223 PJ of unconventional resources (tight and shale gas)[2] are estimated to be

[2] Source: Page 5, WA LNG Industry Profile – Sept-Oct 2017 at http://www.jtsi.wa.gov.au/docs/default-source/default-document-library/wa-lng-profile-0917.pdf?sfvrsn=6. These estimates are different from the AEMO reserve and resource estimates, as updated in Table 5 of its 2017 Western Australian (WA) Gas Statement of Opportunities (GSOO) (AEMO 2017). Priority here is given to the WA Government estimates.

[3] For the purposes of estimating the carbon budget we combine reserve and resource estimates.

located in WA's Canning and Perth basins (see Table 1). Unconventional resources are different from conventional resources because they are developed with significantly different methods such as various forms of hydraulic fracturing. The Canning Basin in the Kimberley region is expected to contain vast amounts of on-shore shale gas that have only come within reach of extraction due to the advances in hydraulic fracking in the recent decade.

In order to fully understand the greenhouse gas contribution that exploiting Western Australia's gas resources would make to the emissions at the national and global level, we estimate the carbon footprint of these reserves and then compare them against the relevant Paris Agreement carbon budgets.

The global carbon footprint perspective provides a basis for comparing the present development of WA's conventional gas reserves and resources and prospective development of unconventional resources for both LNG export and domestic use with the global carbon budget of about 570 $GtCO_2$. that can be emitted to 2050 consistent with meeting the Paris Agreements goals.

The domestic national and WA carbon footprint perspective estimates the fraction of emissions from these developments that would occur domestically and compares them to Paris Agreement-compatible national and WA fossil fuel energy system carbon budgets of about 5.5 $GtCO_2$ and 1 $GtCO_2$ respectively, as derived in this study based on an energy system scenario for Australia.

For the **global carbon footprint**[4] we estimate the release of CO_2 occurring naturally in the reservoir and loss of methane (CH_4) into the atmosphere at any point in the supply and use chain, and the amount of CO_2 emitted at the point of final use combustion[5].

Methane (CH_4), the main component in a gas resource, is a much more powerful global warming agent than CO_2, making the loss of methane to the atmosphere at any point between exploration and final use of a resource a critical variable in estimating both the global and national carbon footprint. The natural CO_2 fraction in gas reserves, which is released to the atmosphere at some point in the supply chain without providing an energy benefit, is of lesser importance but still significant particularly for the domestic carbon footprint.

For the **global carbon footprint** we assume a base methane loss rate for **conventional gas reserves and resources of 1.7% in line with the IEA global estimates. And for unconventional resources with hydraulic fracking where loss rates can be expected to be higher we assumed a base loss rate of 6.5%, which is drawing from recent research in WA. For the domestic carbon footprint we use a slightly different approach for CH_4 losses for conventional gas reserves and resources, which has a lower rate than the IEA top down estimate, and apply the 6.5% loss rate for unconventional resources.**

4 The total amount of greenhouse gas emissions expressed as CO_2 equivalent (CO_2e) https://en.wikipedia.org/wiki/Carbon_footprint

5 We have not included estimates of the small amounts of methane (CH_4) or nitrous oxide (N_20) released in combustion given the significant uncertainties in the primary elements of the carbon footprint assessment.

METHANE LOSS RATES

It is necessary to estimate the overall fraction of methane that is likely to be emitted from the gas reservoir from well to final use, and the emissions of CO_2 from the gas stream, as significant fractions of naturally occurring CO_2 are present in WA gas fields. A full estimate would also account for the fuel used in exploration and other ancillary activities that do not themselves depend on the gas field for energy, however this is beyond the scope of this study. Methane is a much more potent greenhouse gas than CO_2, the rate of leakage or loss of methane from any of part of the gas cycle – exploration, transmission, processing, transport of LNG, regasification and final combustion - is very important for estimating a carbon footprint. Converting one tonne of CH_4 in complete combustion produces around 2.75 tCO_2. A loss rate of 0.5%, meaning that for every tonne of CH_4, 995 kg are converted directly to CO_2, and 5 kg are emitted into the atmosphere as CH_4, increases the warming effect by 4% to about 2.86 tonnes of CO_2 equivalent. Current Australian greenhouse gas inventory estimates loss rates of about 0.5%[6], however there are reasons to believe this may be too low. There are few if any direct estimates of leakage and loss rates from WA natural gas production. The IEA has estimated a global average loss rate at about 1.7%, which would increase the carbon footprint by about 13.5%. Higher leakage rates are discussed in many estimates of life cycle emissions from unconventional gas resources, with estimates of emissions from hydraulic fracking very uncertain and heavily debated, ranging between 2 and 17%. Recent work in WA estimates a possible loss rate of about 6.5% from upstream components of the natural gas production system: with such a loss rate the reserve carbon footprint would be increased by about 50% compared the no leakage case. At present these is a lack of data and analysis of these issues in Australia giving rise to concerns that actual loss rates could be much higher than estimated in present Australia inventories[7].

For both global and domestic carbon footprint estimates we assume a natural CO_2 fraction in WA gas resources at 3.5%, which will ultimately be released into the atmosphere unless captured and placed in geological storage. This adds approximately 3.6% to the carbon footprint. The CO_2 fraction used here is close to the production weighted average of present LNG production facilities. There is wide range: 2-14%. The Gorgon field, for example, is as high as 14%, however it has commitment to capture and store 80% of the CO_2 in the gas flow. Without capture, the production weighted average would increase to about 6.5% at full production, adding a further 3.4% to the carbon footprint of conventional resources. Lack of available data does not permit a better estimate at this time. We have no basis for distinguishing between conventional and unconventional resources in terms of CO_2 content at this time.

With these assumptions, we estimate that the global carbon footprint from the release CO_2 and CH_4 emissions from the full use of WA's conventional gas reserves and resources be equivalent to about 1.3% of the 2018-2050 global carbon budget compatible with the Paris Agreement.

The global carbon footprint of the full development of all WA's proposed unconventional gas resources could release CO_2 emissions equivalent to about 3.4%-5.1% of that budget.

---

6 The NT ginquiry found a range from 0.48% to 0.59%. See Lafleur et al. (2016b). A review of current and future methane emissions from Australian unconventional oil and gas production October 2016, Available at: http://energy.unimelb.edu.au/__data/assets/pdf_file/0019/2136223/MEI-Review-of-Methane-Emissions-26-October-2016.pdf.

7 See for example Lafleur et al. (2016b).

Table 1: Conventional and unconventional gas reserves and resources in Western Australia and associated emissions (global carbon footprint). Source: Government of Western Australia (2017a) *and own calculations.*

Basin	Conventional reserves and resources			Unconventional resources					
	PJ	$GtCO_2e$ 1.7% IEA CH_4 leakage	Fraction of 1.5°C 2050 global budget (570 Gt CO_2)	PJ		$GtCO_2e$ 6.5% CH_4 leakage		Fraction of 1.5°C 2050 global budget (570 Gt CO_2)	
				Low resource	High resource	Low resource	High resource	Low resource	High resource
Bonaparte	17,709	1.17	0.2%	0		0		0.0%	
Browse	37,858	2.49	0.4%	0		0		0.0%	
Canning	1,591	0.10	0.02%	152,704	237,540	13.4	20.8	2.3%	3.6%
Carnarvon	55,249	3.64	0.6%	38,600	43,902	3.4	3.9	0.6%	0.7%
Perth	1,379	0.09	0.02%	30,753	48,780	2.7	4.3	0.5%	0.7%
Total	**113,786**	**7.49**	**1.3%**	**222,057**	**330,223**	**19.5**	**28.9**	**3.4%**	**5.1%**

Notes: In addition to the CO_2 from burning natural gas the main component of which is CH_4we assume an average CO_2 content of 3.5% which is fully released to the atmosphere and a leakage and/or loss of 1.7% of the total contained CH_4 for conventional gas resources and 6.5% for unconventional resources. Due to the much higher Global Warming Potential of CH_4 over natural gas, the CH_4 leakage rate has a very strong impact on the total emissions in CO2-equivalent units.

The global carbon footprint of the Canning Basin unconventional resources is surprisingly large, accounting for 2.3%-3.6% of the global budget, with 3.5% of naturally occurring CO_2 *in situ* and **with a leakage rate of 6.5%.** A lower 1.7% leakage rate of methane still adds up to about 1.8-2.7% of the budget. A leakage rate of 17%, the highest level of leakage discussed in literature, would increase the share to 5.3-7.8% of the global budget

For the **domestic carbon footprint,** we estimate the share of emissions from development of resources that would actually occur in Australia and Western Australia. Gas used abroad as LNG is not recorded as an emission in Australia, nor are the associated shipping or regasification emissions. Direct (upstream) emissions of CO_2 and methane from the exploration and production process, in particular the related fugitive emissions, would occur in Western Australia under any use scenario, even though the pathways to release may be different depending on whether gas is used domestically or for LNG export. Combustion within Australia/Western Australia for power or heating, or in the LNG processing also appears on the national emission accounts.

Greenhouse gas emissions that would occur in Western Australia (and of course Australia) from use of all the presently estimated conventional resources – upstream emissions, CO_2 in the gas stream, domestic use, and LNG processing emissions – are estimated to be in the range of 1.43-1.75 $GtCO_2e$ (about 19 to 23 % of the global carbon footprint). WA domestic emissions differ a little depending on the balance of domestic use and LNG exports, which can be seen in Table 2[8]. A business as usual scenario based on the 2017 AEMO projections extended to 2050 indicates total domestic use emissions[9] at about 0.93 $GtCO_2e$ and LNG related emissions[10] to be about 0.81 $GtCO_2e$. In other words, under current policies emissions from all presently estimated conventional resources related to domestic use are equivalent to about the entire Paris Agreement carbon budget for WA (about 1 $GtCO_2$) up to 2050, even before considering LNG-related emissions.

The full exploitation of presently estimated conventional reserves and resources to fulfil business as usual domestic WA demand, with LNG exports maintained at maximum projected capacity to the mid 2040s, would result in domestic Western Australian GHG emissions exceeding the estimated Paris Agreement budget for WA by 75%.

Table 2 Scenarios for conventional resource domestic carbon gas footprint

	AEMO 2017 Base case WA domestic gas demand projection to 2027 extended to 2050		WA Paris Agreement domestic gas demand and business as usual LNG production	
WA gas pool PJ	113,786	PJ	113,786	PJ
WA Domestic use to 2050	15,820	PJ	9,564	PJ
WA Domestic use combustion emissions	887	$MtCO_2e$	537	$MtCO_2e$
Upstream emissions from WA domestic gas use	41	$MtCO_2e$	25	$MtCO_2e$
Export use for LNG processing and export	97,966	PJ	104,222	PJ
LNG processing emissions (not including CO_2 in gas stream)	562	$MtCO_2e$	598	$MtCO_2e$
Upstream emissions associated with LNG production	255	$MtCO_2e$	271	$MtCO_2e$
Total domestic emissions in WA	1,746	$MtCO_2e$	1,430	$MtCO_2e$
Fraction of WA energy system carbon budget (1 Gt CO_2)	1.75		1.43	

For the period to 2050, this would result in average annual emissions from the projected domestic use of the conventional resources of about 4.8% of 2005 Australian GHG emissions[11], and from the LNG related emissions of about 5.5%. Compared to the **WA emissions in 2005, these average annual emissions make up a much higher fraction: 40% of WA 2005 GHG emissions from domestic gas use and 45% from LNG related emissions.**

While the complete exploitation of conventional gas resources is clearly problematic without massive mitigation measures compared to the emission reduction required to meet the objectives of the Paris

[8] Assuming WA conventional gas does not enter the eastern Australian domestic gas market, which could result in lower LNG exports.

[9] WA Domestic use combustion emissions + Upstream emissions from WA domestic gas use, see Table 2

[10] LNG processing emissions (not including CO_2 in gas stream) + Upstream emissions associated with LNG production, see Table 2

[11] UNFCCC inventory of 597.4 $MtCO_2e$ in 2005 (including LULUCF) http://ageis.climatechange.gov.au/UNFCCC.aspx

Agreement, the scale of unconventional resources is in another class altogether. There are massive amounts of methane and carbon stored in unconventional resources, mainly in the Canning Basin. We use a stylised scenario to illustrate this, assuming that Canning Basin would supply half of Australia's projected business as usual natural gas demand until 2100, via a west-east pipeline (for which pre-feasibility work is underway), with the remainder exported as LNG.

Total Australian domestic emissions from the complete use of unconventional resources could amount to 10.0-18.5 GtCO_2e, equivalent to 17-31 years of 2005 Australia GHG, or 1.8-3.4 times the entire Paris Agreement compatible carbon budget for Australia. Upstream greenhouse gas emissions in Australia would be around 4.0-11.8 GtCO_2e, if all of the resources were to be used. The lower figure results from optimistic assumptions about reduced leakage and loss rates for hydraulic fracturing (fracking), and assuming that flaring and venting emissions would be avoided completely, an overall 50% reduction compared to the base case for upstream emissions. The remaining upstream emissions (4.0-5.9 GtCO_2e,) from unconventional gas production alone would still be comparable to the Paris Agreement compatible CO_2 emissions budget for Australia's total energy system (about 5.5 GtCO_2) for the transition to zero fossil fuel emissions by 2050. Emissions from direct use of gas would amount to about 5.3 GtCO_2e and LNG processing emissions to about 0.7-1.3 GtCO_2e.

Table 3 Illustrative scenarios for unconventional resource use domestic carbon footprint

	Standard upstream emissions and losses case			50% reduction in upstream emissions and losses		
	Low resources	High resources	Unit	Low resources	High resources	Unit
WA Unconventional resource	222,057	330,223	PJ	222,057	330,223	PJ
50% of projected total a domestic Australian gas use scenario to 2100	95,142	95,142	PJ	95,142	95,142	PJ
Domestic use combustion emissions	5,337	5,337	MtCO2e	5,337	5,337	MtCO2e
Upstream emissions from domestic gas use	3,412	3,412	MtCO2e	1,706	1,706	MtCO2e
Total emissions from domestic gas use	**8,749**	**8,749**	**MtCO2e**	**5,043**	**5,043**	**MtCO2e**
Export use for LNG processing and export	126,915	235,080	PJ	126,915	235,080	PJ
LNG processing emissions (not including CO2 in gas stream)	728	1,349	MtCO2e	728	1,349	MtCO2e
Upstream emissions associated with LNG production	4,552	8,431	MtCO2e	2,276	4,216	MtCO2e
LNG export gas production and processing related emissions	**5,280**	**9,780**	**$MtCO_2e$**	**3,004**	**5,564**	**$MtCO_2e$**
Total Australian domestic emissions	**14,030**	**18,530**	**MtCO2e**	**10,048**	**12,608**	**MtCO2e**
Total WA Emissions	**9,111**	**13,611**	**MtCO2e**	**3,004**	**5,564**	**MtCO2e**

Notes: Domestic Australian use scenario is a hypothetical to illustrate the carbon footprint of large scale use of unconventional resources to supply a large fraction (50%) of one plausible Australian gas demand scenario to 2100 used in the body of this report. The WA emissions footprint for this hypothetical scenario assumes all LNG processing is in WA, and about 45% of the approximate 95,000 PJ of Australian demand in this scenario is in WA.

Putting these results together shows quite clearly that using all conventional and unconventional resources is fully inconsistent with climate protection goals, and in particular with a reasonable carbon budget for Australia or Western Australia. Table 4 below shows the results of illustrative scenarios for both conventional and unconventional reserve and resource use.

Under the reference scenario – business as usual domestic Australian gas use and LNG exports – domestic Australian emissions would be around 19.8-24.3 $GtCO_2e$, about four times what Australia is allowed to emit to comply with the Paris Agreement, which is 5.5 $GtCO_2$. Western Australian emissions in the reference scenario for both conventional and unconventional resources would be about 7.8-11.9 $GtCO_2e$, assuming all WA domestic gas comes from these resources and all LNG processing from these resources takes place in WA. In round terms this would be 8-12 times higher than a fair Paris Agreement budget for WA.

In an illustrative scenario where Australia moves to meet the Paris Agreement goals, the overall domestic carbon footprint of the total use of these resources and reserves is lower than in the reference case, given more would be exported. However, there remain very large emissions from LNG processing and associated upstream emissions from gas production, which substantially exceed a reasonable carbon budget for Australia under the Paris Agreement. In this case, because of the larger amount of the assumed LNG processing in Western Australia compared to the reference case, Western Australia's emissions are higher in total than in the reference case.

Table 4 Illustrative Scenarios for conventional and unconventional reserve and resources carbon footprint

Conventional and unconventional resource scenarios	Units	Reference scenario		Paris Agreement pathway	
		Low resources	High resources	Low resources	High resources
WA gas resources	PJ	335,843	444,008	335,843	444,008
Domestic use scenario to 2100 (Australia)	PJ	190,285	190,285	30,301	30,301
Domestic use combustion emissions	Mt CO_2e	10,675	10,675	1,700	1,700
Upstream emissions from domestic gas use		4,680	5,203	745	828
Export use for LNG processing and export	PJ	145,558	253,724	305,543	413,708
LNG processing emissions (not including CO2 in gas stream)	Mt CO_2e	835	1,456	1,753	2,373
Upstream emissions associated with LNG production	Mt CO_2e	3,580	6,937	7,515	11,311
Total domestic Australian emissions	**Mt CO_2e**	**19,770**	**24,270**	**11,713**	**16,213**
Total WA domestic emissions	**Mt CO_2e**	**11,713**	**15,932**	**10,550**	**15,050**

Notes: The emission results are based in the scenarios shown in Tables 2 and 3 above. Domestic Australian use scenario is a hypothetical to illustrate the carbon footprint of large-scale use to supply a large fraction (100%) of one plausible Australian gas demand scenario to 2100 used in the body of this report. The WA emissions footprint for this hypothetical scenario assumes all LNG processing is in WA. Note that the WA component of emissions in this scenario is less than in the Illustrative scenarios for unconventional resource use only (Table 3) as in this scenario WA demand is satisfied first from conventional reserves and resources which have lower assumed CH_4 loss rates.

Figure 1 below shows these results for conventional and unconventional reserves and resources based on a high resource availability scenario, additionally with the effects of reduced leakage and losses on the domestic Australian carbon footprint of these resources. The horizontal line serves as a reference point giving the Paris Agreement-compatible CO_2 budget for the entire energy system for Australia. The bottom part of the respective bars shows the upstream emissions (leaked CH_4 and CO_2 occurring naturally as part of the natural gas) associated with the extraction and processing of the respective amount of gas. The middle part of the bar shows direct CO_2 emissions from domestic use and the uppermost part of the bar depicts the emissions coming from LNG processing.

Even if WA and Australia would reduce the domestic use of natural gas to be in line with a Paris Agreement-compatible scenario (ADV RE), the resulting upstream emissions from LNG exports would be more than twice the Paris Agreement-compatible budget for Australia's entire energy system. In the ADV RE scenario domestic use and upstream emissions associated with LNG exports would amount to about half of that budget.

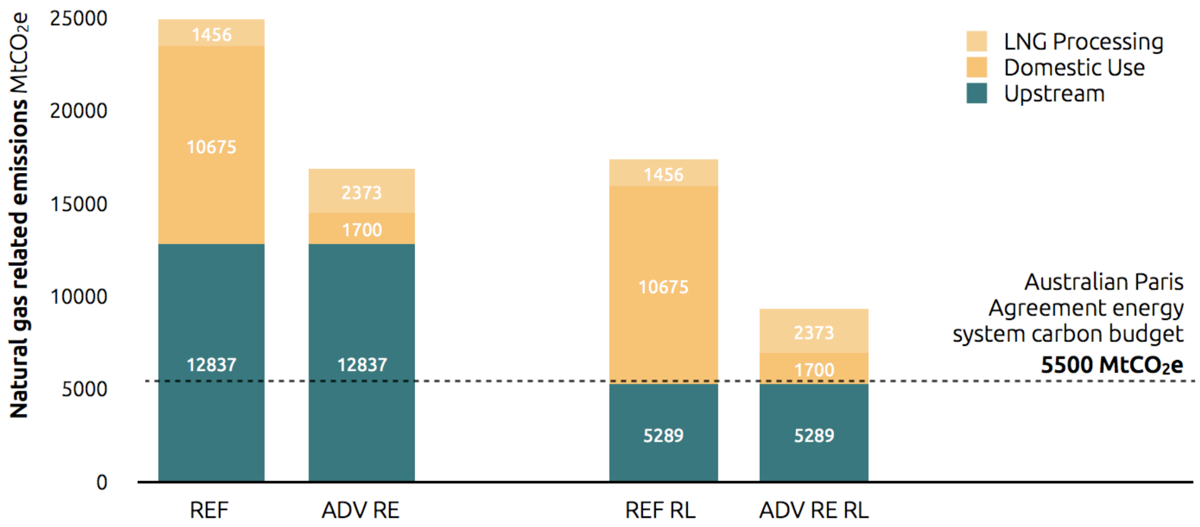


Figure 1 Domestic (Australia) carbon footprint of WA conventional and unconventional gas resource use illustrative scenarios based on the high estimates of reserves and resource availability, with different assumptions about leakage rates (left: base assumption, right: 50% reduced upstream emissions and losses).

As the world moves to meet the Paris Agreement goals, natural gas markets will be affected. Given the scale and significance of Western Australia's LNG exports and the large carbon content of its conventional and unconventional gas resources, it is essential to look at the global demand for natural gas in the context of a climate constrained world.

Energy scenarios that keep global warming below 2°C with at least a 50% probability show that about half the world's proven gas reserves would have to remain unused – let alone the much larger conventional and unconventional gas resources. To examine this issue, we have used the International Energy Agency's recent "Beyond 2°C" scenario (B2DS) as a proxy for a Paris Agreement-compatible scenario. While not fully compliant with the Paris Agreement, it does provide an excellent boundary on likely natural gas demand under climate policies designed to hold warming well below 2°C. In this scenario demand for gas peaks globally around 2025 and declines thereafter, as the world implements the Paris Agreement. In general, in relation to other published energy system scenarios the closer the scenarios get to being in line with the Paris Agreement temperature goal, the faster the decline in gas demand, in particular after 2035. The cumulative global gas demand in the B2DS scenario between 2018 and 2060 is 4299 EJ, which is about 53% of the global proven gas reserves.

The evidence indicates that global gas demand will likely peak and decline within the next 10-15 years as the world implements the Paris Agreement. While there is a role in the energy system for natural gas to displace more carbon intensive energy systems in a transitional mode, the length of this transition is not as long as many assume. It is very important to note that the IEA and other model-based assessments have been consistently underestimating the competitiveness of renewable energy and storage versus gas in the power sector. Renewable energy cost estimates in models often lag significantly behind the market.

There is a risk that further investment in gas production and transport infrastructure will result in a lock-in of uneconomic, carbon-intensive stranded assets. While it seems plausible that in some of the markets for Australian LNG there will be increased natural gas- based electric capacity, it seems very likely that the overall utilisation of technology will reduce below present expectations.

While many modelling assessments assume the deployment of carbon capture and storage (CCS) technology along with gas turbines for power in the future, present real economy technology trends indicate it is unlikely that gas with CCS will be deployed at any scale in future power systems globally as renewable energy alternatives get cheaper and more flexible. Given these trends it is considered extremely unlikely that private sector will invest in fossil CCS technologies in Australia.

Canning Basin and other unconventional gas are not needed in Western Australia or Australia if the country is to meet its Paris Agreement commitments. While gas plays a role for a short transition phase towards a zero-emission energy system, Australia and Western Australia's gas demand in such a transition can easily be supplied without any need to exploiting unconventional gas resources. In a Paris Agreement implementation pathway, gas consumption would start declining by 2030 in the transition phase, and decrease to about zero around 2050. The role of gas in the transition is limited, and eventually, all gas use can be replaced by renewable energy alternatives.

Canning Basin and other unconventional gas are not needed globally. Present day proved reserves are already more than sufficient to fulfil the global demand under energy and emission pathways compatible with the Paris Agreement, In fact, only about half of these reserves can be used by 2050, after which global emissions need to reach net zero. Exploiting Canning Basin and other unconventional gas resources would therefore likely lead to large stranded assets in Western Australia, either through investments for transport within Australia (pipelines) or for export (LNG facilities). Canning Basin gas wells, if considered for export, would be very vulnerable to global price fluctuations, as recently observed in the US shale gas industry. In addition, in a 1.5°C world with much lower demand for gas, competitors will easily undercut costs of Canning Basin production as extraction costs would likely be in the upper end of the global supply cost curve for gas, casting doubt on profitability of these resources.

Opportunity for WA to transition from a fossil to a renewable energy superpower

The Paris Agreement and its implications for global gas markets should be seen as a once-in-a-generation opportunity for Western Australia to use its natural comparative advantage to explore and make use of the vast renewable energy resources and develop a strategy for a transition to a 100% renewable energy future. This could include exporting renewable energy electricity or renewable-energy based energy carriers such as hydrogen, instead of investing into exploration, processing and use of gas.

CONTENTS

INTRODUCTION

Over the last decades, WA has the developed the infrastructure to extract large conventional gas resources both for domestic use and, increasingly, for export as liquefied natural gas - LNG. Domestically this resource has been used to develop an export-oriented mineral mining and processing industry, as well as for use in domestic electricity generation. A total of five LNG export facilities are expected to be operating in Western Australia by the end of 2018, with total production capacity of 49.3 million tonnes per year, accounting for around 11% of global LNG capacity. When these are combined with LNG projects in Queensland and the Northern Territory, Australia would become the world's largest exporter of LNG from 2018, with a total of around one-fifth of total global LNG capacity (AEMO 2016a). Asia is the main destination for most of Australia's LNG exports, with the largest share going to Japan but China in particular is projected to grow in importance (Cassidy & Kosev 2015).

In addition to conventional gas resources in WA, there are vast resources of unconventional (shale) gas, in particular in the Canning Basin in the Kimberley region. These have not been developed for production yet, given the high cost compared to developing conventional gas resources. However, with the rise of hydraulic fracturing (fracking), developing these additional resources for use domestically in Western Australia or for sale to other parts of Australia is under active discussion (WAtoday 2017).

In this report, we examine the global and national greenhouse gas implications of continued development of conventional and unconventional natural gas resources in Western Australia, including in relation to the Canning Basin. We do not explore other environment issues related to this region and development of natural gas resources of any kind. The framing that we apply relates to the Paris Agreement and the scientific implications of its implementation for greenhouse gas emission limitations. The greenhouse gas implications of unconventional resource developments in Western Australia will be examined in the context of global and national carbon budgets consistent with this agreement.

Australia has signed and ratified the Paris Agreement on climate change, together with more than 170 countries. The long-term goal of the Paris Agreement is to limit global temperature rise to "well below" 2˚C above pre-industrial levels and pursue efforts to limit warming to 1.5˚C. To achieve this objective global CO_2 emissions must reach zero by around the middle of the 21st century, GHG emissions a few decades later.

Limiting warming to 1.5°C is particularly important for Western Australia, as it is highly vulnerable to climate change impacts like sea level rise, increased heatwaves and other extreme weather events, fire risk, damages to agricultural production and many vulnerable marine systems, including coral reef loss (Hare et al. 2016). Many serious impacts are already being observed today at about 1°C of warming, and will be much more severe in a 2°C world compared to a 1.5°C world, and are projected to increase rapidly with continued warming (Schleussner, Lissner, et al. 2016). At 1.5°C, the temperature limit in the Paris agreement, impacts and damages are projected to be significantly higher than at present, however by 2°C warming damages for many systems could become extreme. It was this insight that led the world to adopt the "well below 2°C" limit to 1.5° goal in the Paris Agreement.

The Paris Agreement changes fundamentally the balance of economic benefits and risks relating exploitation of fossil fuels of all kinds and is forcing a focus on technologies that have low or zero greenhouse gas emissions. In common with all other countries and regions Western Australia will also need to focus on how to transition its industrial, mining, transport and energy sectors towards zero emissions over the next few decades.

The Paris Agreements means that there is now a major focus globally on avoiding risky investments in further development of fossil fuel resources. While this is most prominent in relation to coal, this also a very important issue for natural gas developments. Natural gas is often referred to and promoted by the gas industry as a transition fuel, or bridge, to a low-carbon economy (see e.g. APPEA (2016)). However, the transition role is limited and often overestimated. Continued investment into the gas sector, in particular liquefaction and transport of LNG, does not take into account the Paris Agreement, in fact creating the risk of breaching it, and will result in stranded assets (Climate Action Tracker 2017b).

At the individual sector level, or in relation to specific resource development - such as the Canning Basin - this translates into fundamental questions about whether greenhouse gas emissions arising from proposed activities or investments are consistent with meeting the Paris Agreement goals.

This report will show that the greenhouse gas emissions arising from development of unconventional natural gas resources in Western Australia are globally relevant, and in particular inconsistent with the Paris Agreement goals. Based on the vast renewable energy resources in Australia and in Western Australia we will examine Paris Agreement compatible energy transformation pathways (and opportunities) and compare the natural gas demand in these against present and prospective resource availability with the development of unconventional resources. This comparison shows that the greenhouse gas emissions impact (carbon footprint) of the development of unconventional Western Australian gas resources could undermine the achievement of climate targets in Western Australia, Australia, and globally.

While the findings of this report challenge many of the conventional assumptions about the future of the natural gas industry it is also important to note that there are major transformational and economic opportunities involved in confronting the challenges posed by the task of dealing with climate change. For this reason, the report concludes by examining the opportunities, as alternatives to the continued expansion of this industry, in a way that is consistent with the globally agreed goals of the Paris Agreement and that take advantage in an economic sense of the low carbon transition begin to be initiated in Asia at present.

Western Australia is not only rich in fossil gas resources but also in renewable energy resources. In fact, Australia is one of the world's best-placed countries to meet its domestic energy demand with renewable sources. The combination of strong solar resources, strong coastal winds and low population density means that Australia – and in particular Western Australia – would have comparatively little difficulty relying completely on renewable energy sources. These factors also result in a high enough potential for economically viable renewable energy for Australia to become a *renewable energy superpower*, with particularly vast renewable energy resources available at competitive prices in Western Australia (BZE 2015).

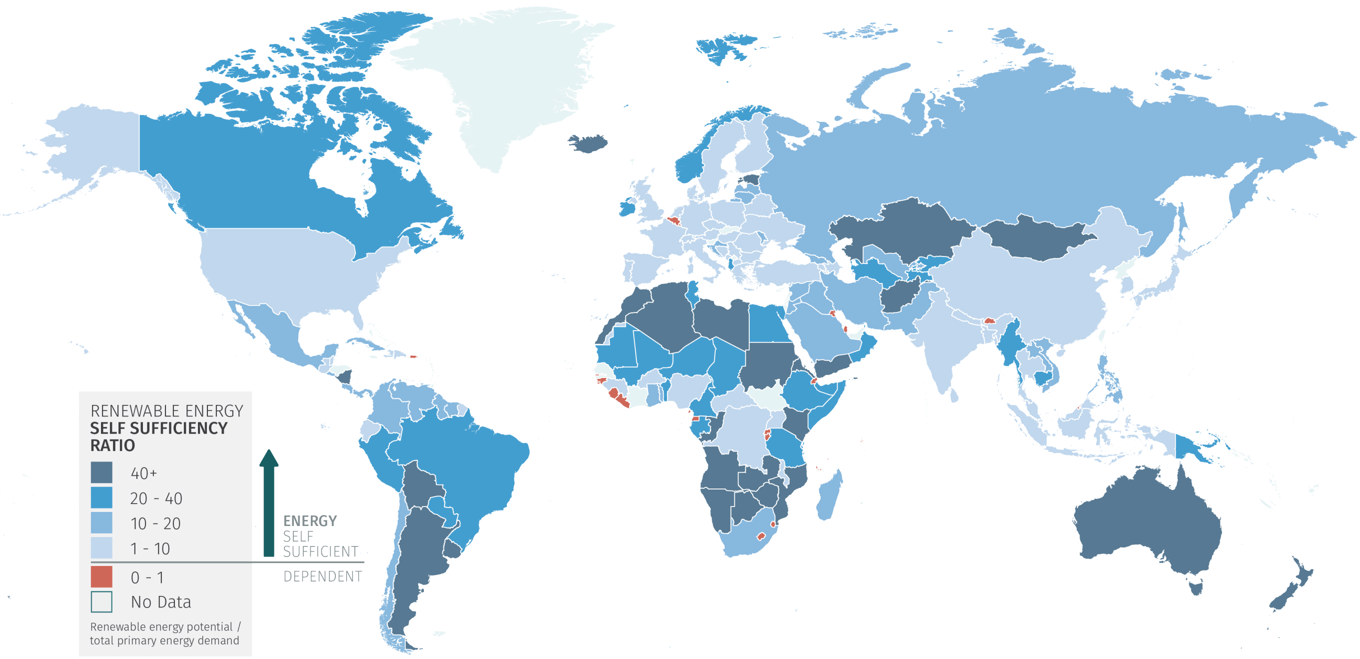


Figure 2: Renewable energy self-sufficiency: How many times could domestic final energy demand by fulfilled from domestic economically viable renewable sources (wind, solar, hydro). Source:(Climate Analytics & UNDP 2016)

WESTERN AUSTRALIA, AUSTRALIA AND THE PARIS AGREEMENT

Western Australia will need to play its role in reducing greenhouse gas emissions over the next several decades, within the context and framework of Australia's evolving policy settings. While its energy intensive sectors will be a relevant consideration in how fast greenhouse gas emissions need to be reduced compared to the national average, ultimately all emissions will need to be reduced towards zero over the next 3 to 4 decades. The absence of a coherent federal policy framework at present to meet the Paris agreement commitments, does not in and of itself exempt Western Australia from considering the commitments of greenhouse gas emissions that would come from specific industrial development proposals. Indeed, many large companies active in Western Australia in the energy and resources sector are exploring transition possibilities for their enterprises to significantly reduce CO_2 and greenhouse gas emissions towards zero over coming decades.

THE AUSTRALIAN CONTEXT

With the ratification of the Paris Agreement in 2016, Australia has committed to undertake "ambitious efforts" (UNFCCC 2015) to achieve its objectives, as well as ensure financial flows are consistent with a low-emission, climate resilient development pathway. Because all signatories recognised that collective efforts and commitments are not yet sufficient to achieve the goals of the Agreement, there is a process of regular stocktaking and review meant to result in the necessary strengthening of national climate pledges.

Australia's present commitments under the Paris Agreement (its Nationally Determined Contribution, or NDC) to reduce emissions 26 to 28% by 2030 from 2005 levels are inconsistent with the long-term temperature goal (Climate Action Tracker 2017a). To be consistent and to ensure a fair and equitable contribution to addressing climate change, greenhouse gas emissions in Australia – and Western Australia - would have to reach zero by the middle of the century or earlier (Climate Action Tracker 2017a; CCA 2014).

Instead, Australia's emissions are increasing. Actual policies are not even sufficient to meet the already inadequate NDC target, and would lead to an 8-16% increase in emissions over 2005 levels by 2030 (excluding the very uncertain land use and land-use change emissions). If all governments were to follow Australia's approach, the world would warm by 3 to 4°C by 2100 (Climate Action Tracker 2017a).

LNG PROCESSING EMISSIONS

The rapid expansion of LNG processing across the country is a major factor in the emissions increase over the last three years, with further growth in the LNG sector expected as new plants come online in 2018, mainly in Western Australia. LNG production is expected to grow nearly 200% between 2015 and 2020, which would lead to an 85% increase in direct combustion emissions from the energy sector in those five years, most of it in Western Australia (Australian Government 2017).

Emission related to LNG production and processing are estimate to be rapidly increasing and were about 11 $MtCO_2$ in 2015 (about 1.9% of national GHG emissions in 2005) and are projected to increase by 2.5-fold by the early 2020s or 5% of 2005 Australia GHG missions, as new LNG plants ramp up to full production (Australian Government 2017).

Fugitive emissions from LNG processing depend on the carbon dioxide content of the raw gas stream. Carbon dioxide within the raw gas stream needs to be removed to create LNG, and some gas resources have very high *in situ* CO_2 components. There is a risk that emissions could be much higher than projected above, if abatement measures, such as CCS, which was planned for the Gorgon plant, fail to deliver. According the recent Review of Climate Change Policies (Commonwealth of Australia 2017a), 3 to 4 Mt CO_2eq were supposed to be injected each year, but this has not been implemented yet (The Western Australian 2017), leading to additional emissions that have not been taken into account in recent emissions projections.

While there is no plan at federal level to reduce greenhouse gas emissions beyond the 2030 target, almost all of Australia's States and Territories – representing about 82% of present day Australian population – set goals to achieve net zero emissions by 2050 (Climate Council 2017). The only exceptions at present are Western Australia and the Northern Territory. In fact, Western Australia is now the only state or territory without a target to increase renewable energy or achieve net zero emissions by 2050 (Climate Council 2017).

NATURAL GAS IN WESTERN AUSTRALIA

Western Australia (WA) has globally significant natural gas resources. Almost all (more than 90%), or 113,786 PJ[12], of Australia's total estimated conventional gas resources are located onshore and offshore in WA (AEMO 2017). In addition, between 222,057 and 330,223 PJ of unconventional resources (tight and shale gas) may be located in WA's Canning and Perth basins (Government of Western Australia 2017a) (see Table 5).

Unconventional resources are different from conventional resources because they are developed with significantly different methods, like various forms of hydraulic fracturing (Haluszczak et al. 2013). Given the significant amount of conventional gas resources remaining and the relatively high cost of developing unconventional gas, there has been no commercial production of unconventional gas in WA yet (AEMO 2016a).

Particularly, the Canning Basin in the Kimberley region is expected to contain vast amounts of on-shore shale gas that have only come in reach of extraction with the rise of hydraulic fracking in the recent decade (Bista et al. 2017). Estimates are very uncertain. (AEMO 2016a) refers to an estimate of a volume of 235 trillion cubic feet (tcf) of shale gas (249,205 PJ) and 22.5 tcf (23,542 PJ) of tight gas in the Canning Basin. A recent Australian Energy Resource Assessment estimate (Geoscience Australia 2016) of the undiscovered potentially prospective resources gives a total of 452 tcf (479,321 PJ), assuming only a 5% recovery of the total estimate at 50% confidence level. The Government of Western Australia (2017a) estimates 70-150 tcf (74,231-159,067 PJ) of shale gas and 74 tcf (78473 PJ) of tight gas to be contained in the Canning basin. The estimates from Government of Western Australia (2017a) are also used in the most recent publication by AEMO (2017), which is why we adopt them for the purpose of this report. These resources add to the overall large gas resources of Australia as a whole.

WA consumes more gas domestically than any other state in Australia, despite its relatively small population. In 2015-16, WA's domestic gas consumption was 561.8 petajoules (PJ), accounting for around 37% of Australia's total gas consumption (AEMO 2017).

---

12 Source: Page 5, WA LNG Industry Profile – Sept-Oct 2017 at http://www.jtsi.wa.gov.au/docs/default-source/default-document-library/wa-lng-profile-0917.pdf?sfvrsn=6. These estimates are different from the AEMO reserve and resource estimates, as updated in Table 5 of its 2017 Western Australian (WA) Gas Statement of Opportunities (GSOO). Priority here is given to the WA Government estimates.

In WA gas is consumed mostly by large industrial and mining users, the mineral processing sector, and for electricity generation. Residential consumption accounts for a small proportion of total gas use (around 3%) (AEMO 2017). Together, large customers account for two-thirds of gas used in WA, with the majority used in the mineral processing (e.g. alumina, nickel, lithium) (32%), electricity generation (29%), and mining (23%) sectors (AEMO 2017).

WA's domestic gas demand (without LNG exports) is expected to only grow at a very low rate of 0.3%p.a. This demand projection explicitly does not take into account the Paris Agreement emission reduction commitment and any possible reduction in demand expected from it. Potential gas supply is forecasted to stay ahead of today's demand of under 1100 TJ/day[13], with assumed continuation of development of gas reserves, including the Gorgon and Wheatstone domestic gas production facilities (AEMO 2017).

WA's domestic gas market is expected to be well supplied even under a business-as-usual scenario that does not take into account the Paris Agreement, with potential gas supply expected to remain higher than forecasted gas demand over the outlook period up to 2026.

State greenhouse gas inventory data are not available after 2015. However, even by 2015, the increase in fugitive emissions from gas production is very high and can be expected to grow considerably in 2016, 2017 and beyond.

EMISSION TRENDS IN WESTERN AUSTRALIA

Western Australia's economy relies heavily on mining of natural resources, which generated 23% of total value added in fiscal year 2015-2016. Mining was also the fastest growing sector. By far the biggest component of the mining industry is the mining and export of iron ore with AU$ 64 billion sales in 2016-2017, followed by LNG with nearly AU$ 13 billion. Both sectors have grown strongly over the past years with Western Australia now being the source of 9% of global LNG exports (Government of Western Australia 2017b).

The heavy dependence on the resource extraction and export is reflected in the sectoral composition of GHG emissions: In 2015, nearly 23% of emissions came from the mining sector which makes it the second largest contributor after the electricity sector (28%). Deepening this reliance would also mean that the associated emissions would rise.

[13] Note that the AEMO implied annually demand for gas in WA (excluding that for LNG processing) is significantly lower than the data available from Department of the Environment and Energy, Australian Energy Statistics, Tables F and R, August 2017. This appears to relate to different methodologies and accounting units adopted by AEMO and the underlying Marsden Jacob Associates report (https://www.aemo.com.au/-/media/Files/Gas/National_Planning_and_Forecasting/WA_GSOO/2017/MJA-Methodology-Report.pdf) compared to the Department of Environment and Energy. We have applied AEMO growth rates were appropriate to the official Australian energy data for Western Australia.

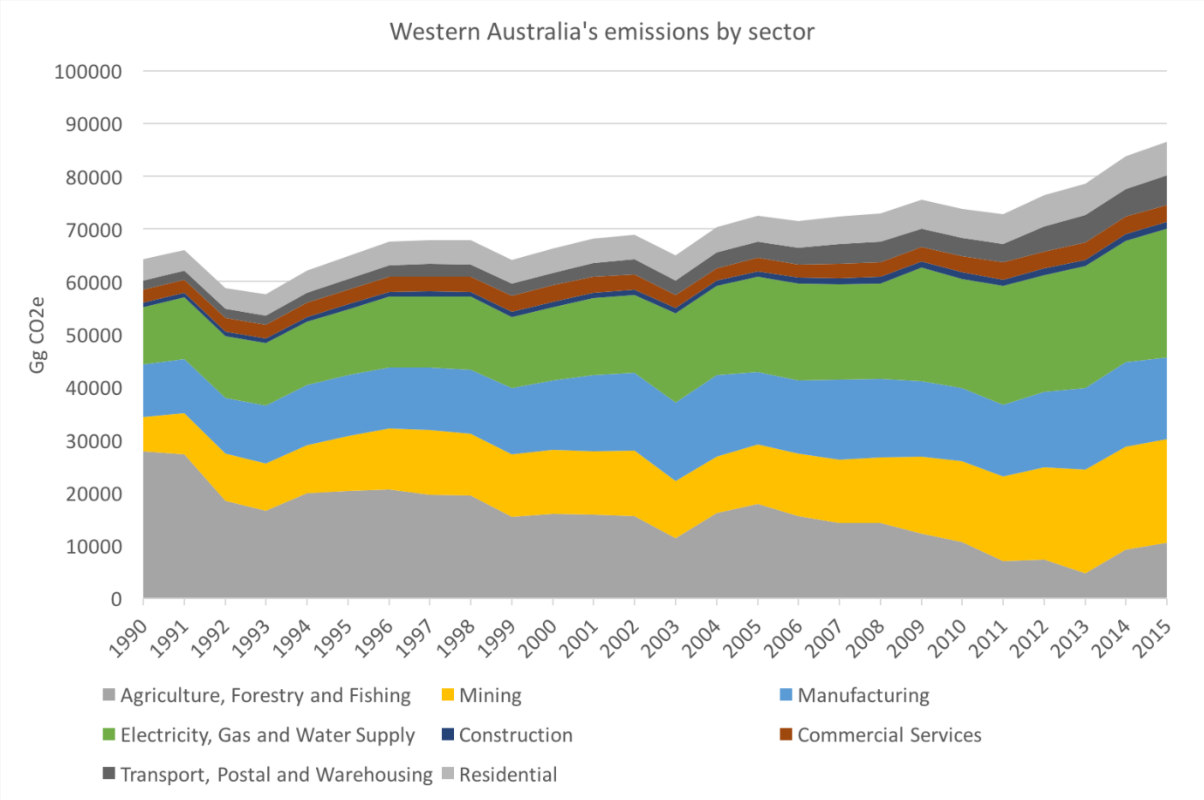


Figure 3: Western Australia's emissions by economic sector. Source: Australian Government (2017)

Western Australia's emissions are rising sharply (more than in any other state or territory, *Commonwealth of Australia (2017b)* (see Figure 3). Emission from most sectors rose between 2000 and 2015. Fugitive emissions – mostly related to natural gas production – rose 47% between 2000 and 2015 (from 5.02 to 7.34 $MtCO_2e$). These latest inventory figures for Western Australia do not include the rise in emissions in 2016 and 2017 to be expected from the large-scale increase of LNG export projects during this time. Given these developments, there is an **urgent need for Western Australia to develop a strategy to account of the Paris Agreement the need to reduce CO_2 emissions to zero by around 2050.**

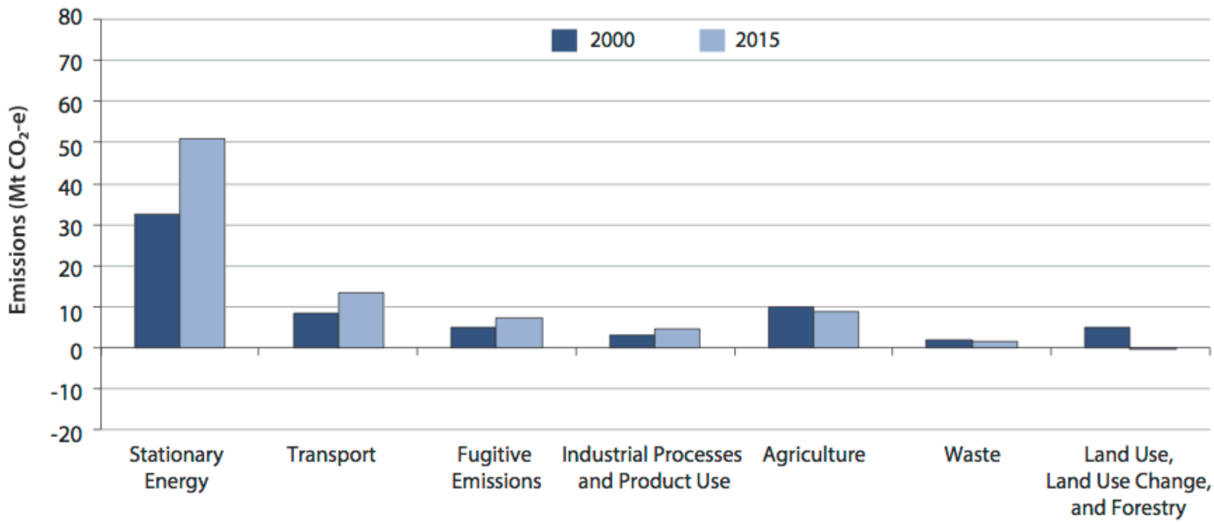


Figure 4: Western Australia, annual emissions by sector, 2000 and 2015. Source: Commonwealth of Australia (2017b)

HOW MUCH GAS DOES THE WORLD NEED?

Given the scale and significance of LNG exports for Western Australia, as well as the uncertain market for any natural gas developed from the Canning Basin it is important to look at the likely future of natural gas demand globally as the world moves to meet the Paris Agreement goals.

In examining likely global energy scenarios consistent with the Paris Agreement, we have chosen to focus on the International Energy Agency's recent assessments, which come close to modelling the required changes to meet the Paris Agreement's 1.5° limit. The IEA is internationally recognised as an authority in the area, and while there are other studies that could be used, including forthcoming energy system model assessments for the 1.5°C IPCC Special Report due in October 2018, the broad results are consistent with a wide range of studies.

Figure 5 shows global gas demand projections until 2060 from the International Energy Agency's (IEA) report Energy Technology Perspectives (ETP) (IEA 2017a). The Reference Technology Scenario (RTS) is the baseline scenario, assuming the implementation of present day climate change mitigation commitments (NDCs and other). The 2°C scenario (2DS) includes assumptions on additional mitigation action that would result in a 50%[14] chance of keeping anthropogenic global warming to below 2°C above pre-industrial levels by 2100. The Beyond 2°C scenario (B2DS) achieves an average warming of 1.75°C above pre-industrial with 50% likelihood. This scenario is used as a proxy for a Paris Agreement compatible scenario, as at present only very few other scenarios that adequately depict the Paris Agreement long-term goal of limiting global warming to 1.5°C using up to date technology assumptions are available (Schleussner, Rogelj, et al. 2016).

[14] Due to uncertainty in the response of the Earth's climate to rising levels of GHGs, this probability is usually computed using a probabilistic emulator of state-of-the art climate models (Meinshausen et al. 2011; Meinshausen et al. 2009).

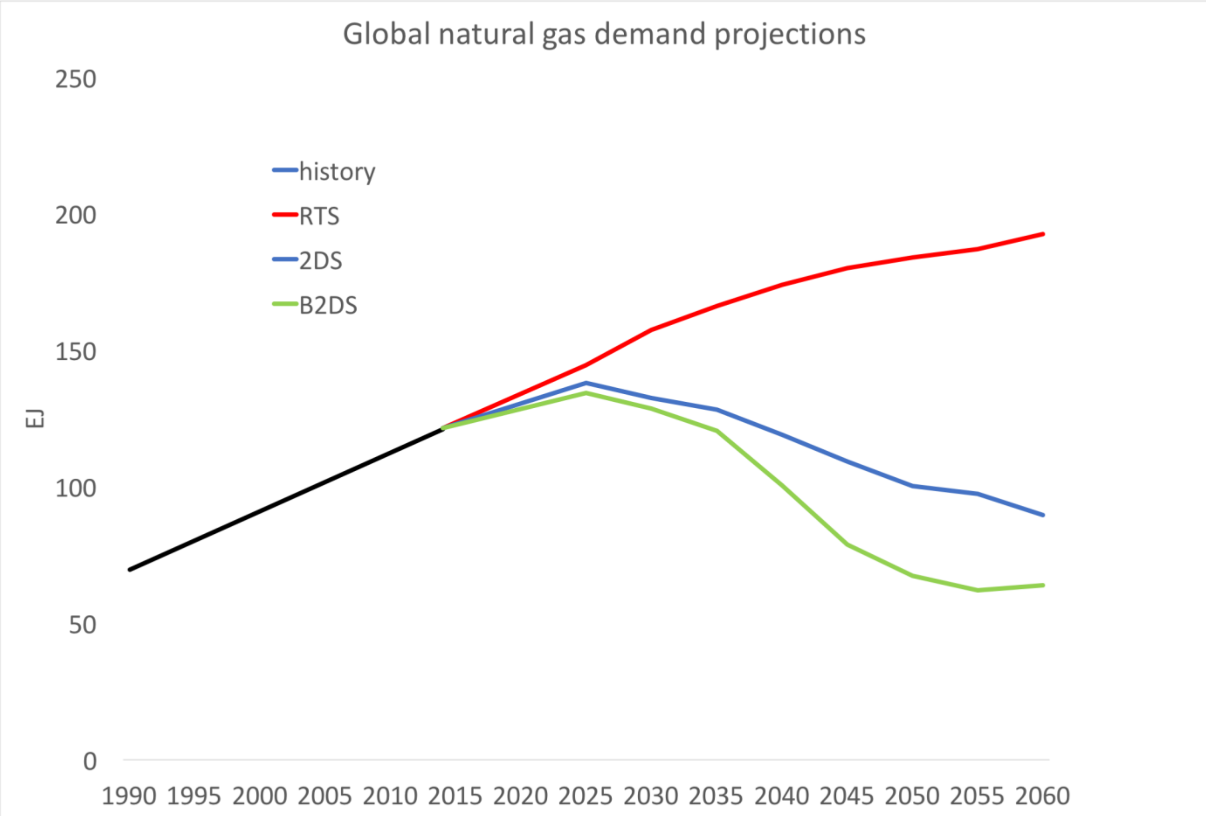


Figure 5: Projections for global gas demand without ambitious climate policy (RTS) and with climate policy aiming for stabilisation at 2°C (2DS) and "well below" 2°C (B2DS). Source: IEA Energy Technology Perspectives (2017)

In these scenarios demand for gas peaks globally around 2025 and declines thereafter, as the world implements the Paris Agreement. In general, the closer the scenarios get to being in line with the Paris Agreement temperature goal, the faster the decline in gas demand, in particular after 2035.

The IEA assumes economic viability and application at scale of carbon capture and storage (CCS) technologies to gas turbines in the power sector from the 2030s to achieve the necessary reductions while continuing to use fossil gas. Electricity generation from gas without CCS is phased out almost entirely by 2060 in the B2DS scenario.

It is important to note that gas power plants with CCS are not zero emissions power plants: there are still methane emissions during production and transport emissions. Assuming a leakage (fugitive emissions) between 0.8 and 5.5%, life cycle emissions of gas power plants with CCS can range between 90 and 370 gCO_2eq/kWh (IPCC 2014).

We view the IEA assumptions about future economic viability and application of CCS at scale in fossil fuel applications as highly questionable given present real economy and technology cost trends. Cheaper and more flexible renewable energy production and storage alternatives are already beginning to outcompete new gas generation capacity. CCS would simply add a higher cost loading and increase the growing competitive disadvantage of gas generation capacity.

The IEA and other model-based assessments have been consistently underestimating the competitiveness of renewable energy versus gas in the power sector, and, for example, the role of solar photovoltaic technology (Creutzig et al. 2017), with renewable energy cost estimates in models often lagging significantly behind.

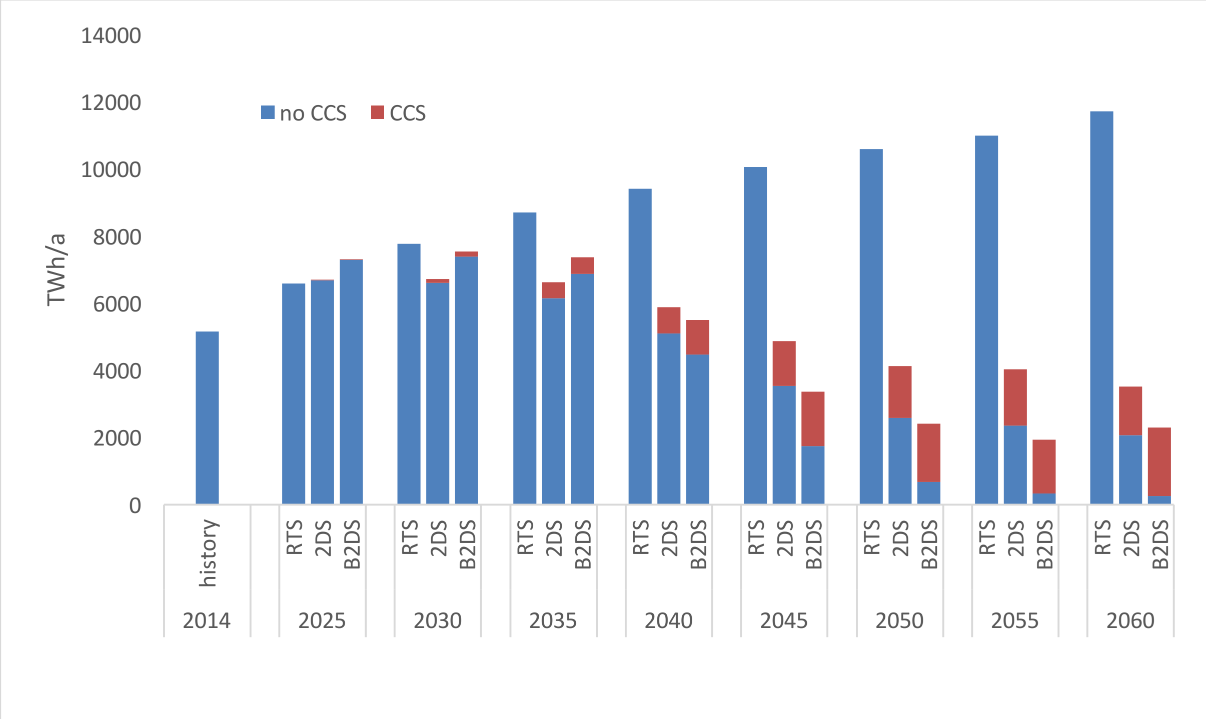


Figure 6: Projections for global electricity generation from gas without ambitious climate policy (RTS) and with climate policy aiming for stabilisation at 2°C (2DS) and "well below" 2°C (B2DS). Source: (IEA 2017a)

It is therefore highly unlikely that gas with CCS will be deployed at any scale in future power systems globally. While it seems plausible that in some of the markets for Australian LNG there will be increased installed natural gas fired electric capacity, it seems very likely that the overall utilisation of technology will reduce, further reducing the incentive to install CCS technologies. Given present technology trends it is considered extremely unlikely that private-sector investment will occur in fossil CCS technologies in Australia. Future gas demand in a world implementing the Paris Agreement is likely to be lower than in the IEA B2DS scenario shown in Figure 6.

The cumulative global gas demand in the B2DS scenario between 2018 and 2060 is 4299 EJ, which is about 53% of the global proven gas reserve of 8089 EJ (IEA 2017c)[15]. This confirms earlier studies (McGlade & Ekins 2015) that concluded that even **for a scenario that keeps global warming below 2°C with at least a 50% probability, globally, about half of gas reserves would have to remain unused until 2050 – let alone the much larger conventional and unconventional gas resources.**

The expected decline in demand for gas under the Paris Agreement in the next 10-15 years puts in question the economic viability of investments into further LNG exports. Currently planned and projected rates of LNG exports (about 1.3 EJ/a from Eastern and South Eastern Australia until 2026 (AEMO 2016b), and increasing from 2.4 EJ/a in 2017 to between 3.3 and 4.1 EJ/a in 2027 from WA, (AEMO 2017)) may not be able to be sustained economically if global gas demand peaks in the 2020s, before declining by 2030. As a consequence, there is a risk of asset stranding. In this scenario, Australian LNG exports at a rate of about 6 EJ/a beyond 2025 would need to secure a constantly

15 We use the energy density estimate of natural gas given in (AEMO 2016a) of 37.45 PJ/bcm to convert the 216 tcm of (IEA 2017c) to estimate its energy content.

growing market share – reaching 6-8.5% of total global natural gas demand in the IEA B2DS Scenario in 2040/2050.

At the least this Paris Agreement scenario cast doubts on the economic and environmental wisdom of further investments into exploration and extraction of unconventional gas resources like the Canning Basin in Western Australia. Given, as will be shown below, that these are not needed for domestic use, they would have to be processed and exported as LNG. As the extraction cost of Canning Basin shale gas will likely be on the upper end of the global supply cost curve for gas (McGlade & Ekins 2015), and the costs of exporting it as LNG would add to these, profitability of Canning Basin gas wells, if considered for export, would be very vulnerable to global price fluctuations, as could recently be observed in the US shale gas industry. In addition, in a 1.5°C world with much lower demand, competitors will easily undercut costs of Canning Basin production.

HOW MUCH GAS DOES WESTERN AUSTRALIA NEED?

The previous section showed that there is no strong case for additional natural gas resources beyond those presently available to facilitate a low carbon transition globally. In this section, we look at what the domestic demand in Australia and Western Australia could look like in a Paris Agreement energy transformation.

DECARBONISING POWER, TRANSPORT AND INDUSTRY SECTORS

All expert assessments show that the energy sector, and within that, the power sector, needs to – and can – decarbonise much faster than other sectors. To limit warming to 1.5°C, the energy sector needs to decarbonise by mid-century, with the power sector reaching zero emissions globally by 2050 (IPCC 2014; Rogelj et al. 2015). This is also confirmed by the IEA in its 2017 Energy Technology Perspectives report (IEA 2017a). Full decarbonisation of the power sector is also a key strategy to decarbonise other sectors through large-scale electrification in the building, industry and transport sectors, and using opportunities of sector coupling. This is a robust finding – both globally (IPPC 2014; Climate Action Tracker 2016) as well as for Australia (Climate Change Authority 2016; ClimateWorks Australia 2014b; Hare et al. 2017).

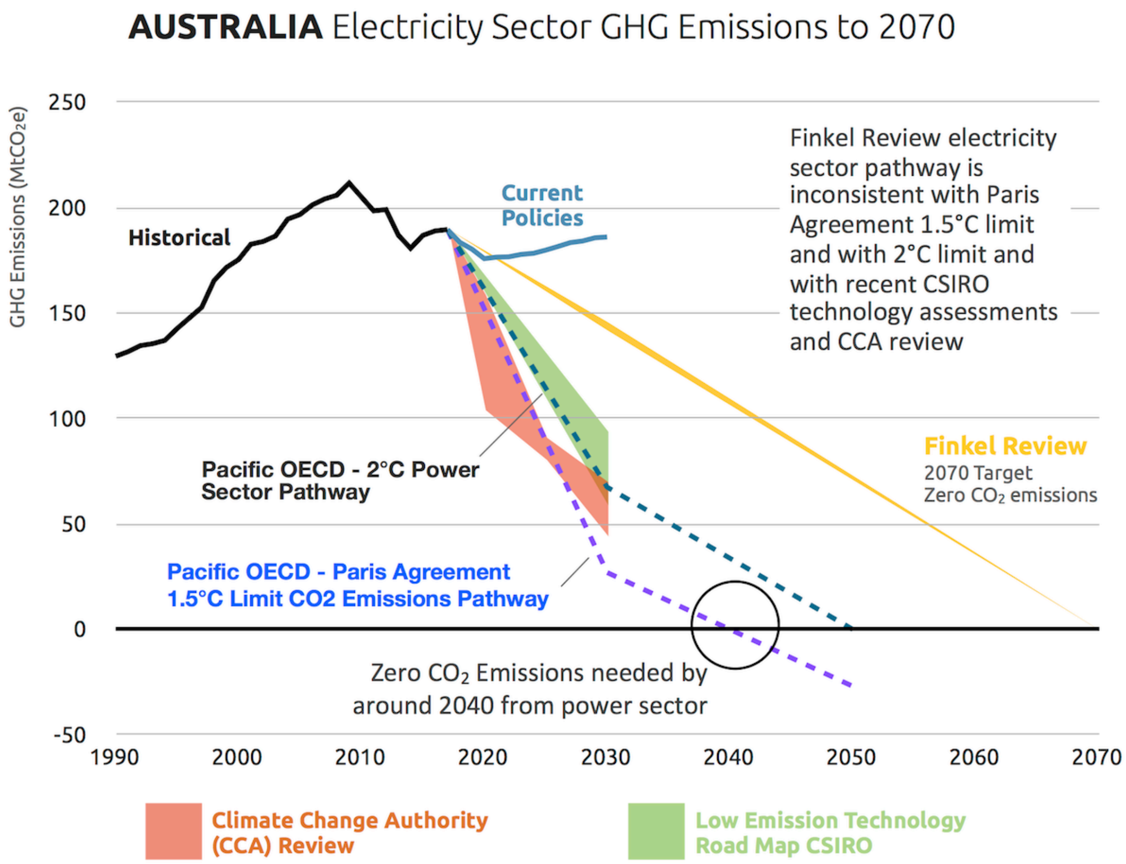


Figure 7: Australian Greenhouse gas emissions from the electricity sector
Historical and current policies projection, Pledge, based on Climate Action Tracker (2017a), Commonwealth of Australia (2016) and recommendation by the Climate Change Authority (CCA 2014) as well as the resulting emissions from the CSIRO Low Emissions Technology Roadmap. An indicative least-cost pathway for the Australian electricity sector consistent with the Paris Agreement 1.5°C limit has been inferred from the MESSAGE IAM Model from its PAO - Pacific OECD – region comprising Australia, New Zealand, Japan (IIASA 2017). This involves emissions reductions of about 85% in 2030 and zero emissions by 2040 (Rogelj et al. 2015; Rogelj et al. 2013). A pathway consistent with limiting global warming to below 2°C indicates reductions required of about 65% in 2030, reaching zero CO2 emissions by 2050. See Hare et al. (2017) for further details.

Many studies have shown the technical and economic feasibility of decarbonising the power sector and a transition to 100% renewable energy. They mostly take into account additional electricity demand resulting from a contribution to decarbonisation of heating, transport and industry sectors through electrification, and look at different options for providing reliability and grid stability, including storage options (Riesz et al. 2016; ENA 2017; Blakers et al. 2017, see also ACOLA, 2017). Studies also looked at the feasibility of full decarbonisation of heating and cooling demand for buildings and industry (ClimateWorks Australia 2014a; BZE 2017).

To estimate Australia's domestic need for gas following a pathway consistent with the Paris Agreement, we analysed a published scenario for decarbonising Australia's energy sector by 2050, with a fully renewable-based energy supply system – including transport and industry - and with existing electricity demand supplied by renewable energy by 2030 (Teske et al. 2016) (see Figure 8).

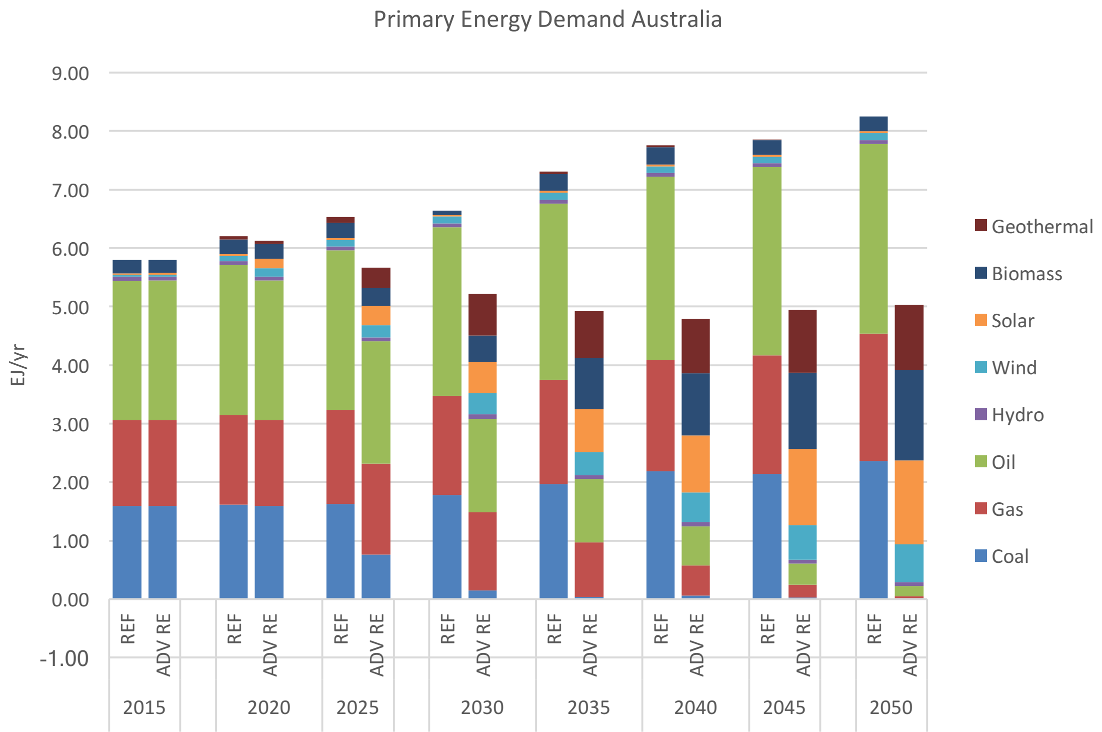


Figure 8: Australian primary energy demand by fuel/source for a business-as-usual - Reference (REF) and Advanced Renewable Energy (ADV RE) scenarios. Source: Teske et al. (2016)

In this "Advanced Renewables Scenario" (ADV RE), coal as the most emission-intensive fuel is phased out completely in the early 2030s and coal power plants shutting down by 2030. This is in line with the analysis by Climate Analytics (2016) on Paris Agreement-compatible coal phase-out pathways. Natural gas continues to play a role in a transition period, replacing coal and generating additional electricity to decarbonise the industry and transport sectors. However, demand starts declining in this scenario around 2030 and only very small shares of gas would be left in 2045, as it would be replaced over time either by electricity from renewable energy or by biofuels and other, synthetic fuels derived from renewable energy.

The major energy sources in the Advanced Renewable Energy scenario in 2050 are solar, biomass, wind and geothermal energy, and Australia is extremely well endowed with all of these. Electricity use doubles by 2050 in the industry sector due to electrification replacing direct fuel consumption.

Similarly, the transport sector relies mostly on electric mobility. Resulting higher investment costs over the whole period would be compensated by power and transport fuel savings (Teske et al. 2016).

So far there has been no comprehensive study on transformation towards zero emissions of all energy-related sectors in Western Australia, including transport and industry. However, the conclusions based on the studies for the overall Australian energy sectors also apply to Western Australia.

SHORT NATURAL GAS TRANSITION IN THE POWER SECTOR

An analysis of a range of studies and cost estimates of 100% renewables studies for Australia (Riesz et al. 2016) shows that a gas transition, relying on baseload gas using high-efficiency closed cycle gas turbines (CCGT) is unlikely to be cost-competitive with wind generation for bulk production of electricity. Gas fired peaking generation (such as lower-efficiency open cycle gas turbines, OCGT) could be an exception, possibly providing peaking and backup capacity in a transition period, which, due to their rare operation, would not contribute significantly to gas demand. As costs of renewable alternatives, such as wind or solar with battery storage, continue to drop, this might even be unnecessary in the near future (Lazard 2017).

An analysis of different options for an 85% or even complete decarbonisation of electricity supply by 2030 for Western Australian South West Interconnected System (SWIS), (Laslett et al. 2017; Rose et al. 2016) focuses on ensuring reliability and grid stability, including a combination of energy efficiency measures and currently available technologies such as residential and commercial roof top photovoltaic systems, solar thermal power stations with heat storage, wind power and distributed battery storage systems. Laslett et al. (2017) also looks at a new technology option for longer-term storage of excess electricity by producing gas - so called “Power-to-Gas” technology, which is still under development. It can build on the gas infrastructure in Western Australia, using the ample solar and wind resources for electricity. Other options studied are wave power (presently in development stage) and biomass (from oil mallee) to replace natural gas, as well as pumped hydro storage. These studies also assume an increased electricity demand due to an increased uptake of electric vehicles. They confirm what has been shown for other parts of Australia or other countries and globally: gas can play a limited role in a transition phase to 100% renewable energy, but with a declining share in electricity generation, given gas capacity would be mostly used to cover periods of low variable renewable energy power.

RENEWABLE ENERGY ALTERNATIVES EXIST FOR ALL APPLICATIONS OF INDUSTRIAL GAS USE

Looking beyond power generation, existing gas demand in industry and mining can be eventually replaced by renewables, as was shown in the Teske scenario. This will be particularly important in Western Australia, given that its economy relies heavily on mining and industry, which next to electricity generation are the largest gas consumers and also important sources of increasing greenhouse gas emissions. There are renewable energy options for all these uses of gas in Western Australia. Examples are ammonia production from renewable energy (“green ammonia”, see IEA (2017b)) and its present use in fertiliser industry, and options for export, e.g. in the Pilbara region (see section above, (IEA 2017b; ARENA 2015; ACOLA 2017).

Hydrogen can also serve as an additional renewable fuel option for high-temperature applications in the industry sector, together with biomass. Gas can also be replaced by renewably-produced hydrogen as feedstock for ammonia production. The IEA has pointed out the vast opportunities in Australia based on the “extreme abundance of solar and wind resources” to spur international trade in renewables-based, hydrogen-rich chemicals and fuels (IEA 2017b). Renewable energy alternatives exist for all applications of industrial gas use, not only for power generation but also for lower output temperatures and high temperature thermal processes as well as chemical feedstock, as studied by ARENA (2015).

Beyond addressing domestic needs and using comparative advantages in energy-intensive production processes like aluminium smelting, Western Australia can become an exporter of renewable energy in the form of hydrogen, or hydrogen bound in ammonia (Turner 2017) or methane (Shahan 2017; Veselovskaya et al. 2017). Options for a power grid connection to South East Asia have also been studied (Gulagi et al. 2017; Mella et al. 2017; Parkinson 2017). This opens up opportunities particularly in Western Australia.

In relation to the LNG export industry a large part of existing gas demand in Western Australia includes gas used for LNG processing, which is projected to increase substantially due to the enormous amounts of projected LNG exports. As we have seen from the preceding analysis there is a large question mark over how long gas resources in Western Australia can exported as the world implements the Paris Agreement, with a likely peak in demand in the 2020s followed by a decline in the 2030s.

TRANSPORT – ELECTRIFICATION AND OTHER RENEWABLE ENERGY OPTIONS

Options and opportunities to accelerate the shift to public transport in metropolitan areas, as well as a shift to electric cars have been studied extensively (BZE 2014; BZE 2016). The electric vehicle market is in rapid shift as new players drive down costs (China) and others overcome technological difficulties (such as Tesla). The latter drive technological development and the benefits will become available to a broader market soon. A recent market estimate (BNEF 2017) expects electric vehicles to accelerate to 54% of new car sales by 2040 globally, as tumbling battery prices lead to lower lifetime costs and purchasing price compared with internal combustion engine cars in most countries by 2025-29 (BNEF 2017).

For freight transport, some studies (see e.g. ClimateWorks Australia 2014) assume that natural gas can provide an alternative fuel e.g. for trucks. However, this would not achieve the necessary full decarbonisation. Instead, renewable hydrogen (produced with renewable electricity) and sustainable synthetic fuels (synfuels) can substitute gas and make up a significant share of transport fuels. The Advanced Renewable Energy Scenario analysed in Teske et al. (2016) relies on increased efficiency and a shift to rail, in particular in large metropolitan areas, as well as to electric vehicles, biofuels, and, eventually, after 2030, hydrogen and synthetic fuels generated using renewable electricity. New electric truck technologies entering the market now may also have a big effect on the decarbonisation of this sector, with significant benefits in Western Australia (REneweconomy 2017a).

WESTERN AUSTRALIAN GAS DEMAND IN A PARIS AGREEMENT CONSISTENT SCENARIO

Consistent with the scenario analysed above for Australia, we use Teske et al. (2016) as a benchmark scenario to assess the gas demand in Western Australia for a Paris Agreement driven transformation of the energy system towards nearly 100% renewables. We downscale this scenario to WA by applying the respective all-Australian growth rates for total gas use and electricity output from gas fired power plants to the last point in the historical data series of gas use for Western Australia.

This scenario assumes that the power sector is decarbonised by around 2035 and with an electrification of much of the energy use in transport, buildings, and industry.

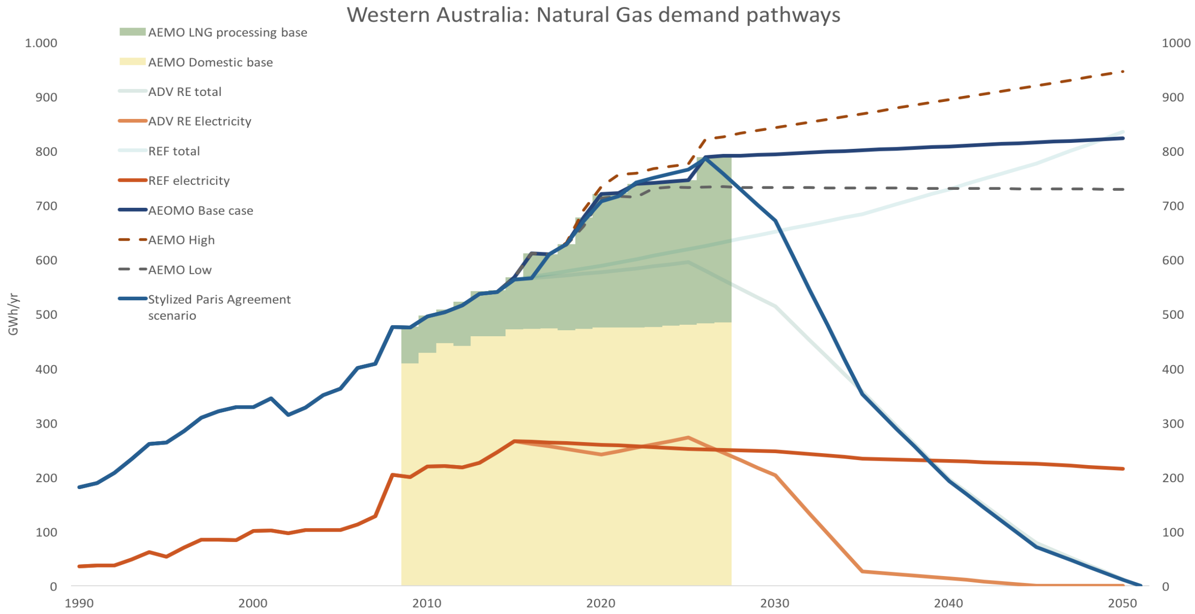


Figure 9:Business as usual (REF, AEMO base), Advanced Renewable Energy (ADV RE) scenario for gas use in Western Australia. Sources: (Australian Bureau of Statistics 2016; Teske et al. 2016; AEMO 2017)[16], *own calculations.*

Gas that is not used for electricity includes gas used in industry, and for LNG processing (around 9% of the total input volume of liquefied gas production is used for this). The latter is a significant amount due to the enormous amounts of LNG that are projected to be exported. *Domestic* gas demand includes gas for electricity generation, but also for other uses, in particular industry. While domestic gas demand is projected to stay roughly constant until 2026, gas exports are expected to rise under any of the official scenarios in (AEMO 2016a) and the amount of gas used for LNG processing would therefore soon make up a large part of the overall gas use within the next decade.

From Teske et al. (2016), we can derive the cumulative demand for natural gas for each of the scenarios as well as the cumulative energy related greenhouse gas emissions for each scenario.

Under the reference scenario without additional climate policy and assuming a further increase in gas demand, Australia as whole is projected to use about 190 EJ of gas by the end of the century (Figure 10). This is equivalent to about 40% of Western Australia's estimated conventional and unconventional gas resources.

In the Paris Agreement-compatible ADV RE scenario, natural gas is phased out around 2050, resulting in a cumulative Australia wide gas demand of about 30 EJ. This ADV RE demand is equivalent to one fifth of presently estimated conventional resources or less than one tenth - 6% - of Western Australia's total estimated (conventional and unconventional) gas reserves. The overall cumulative energy related emissions in this scenario for the period 2018-2050 is about 5.5 $GtCO_2$

[16] AMEO projections are to 2027 and we have extended to 2050 by extrapolation (LNG processing) or trend (domestic demand). LNG production levels are held at 2027 levels and domestic demand extrapolated in a trend basis for illustrative purposes. Updated with AEMO, 2017. *Gas Statement of Opportunities for Western Australia. December 2017*, Available at: https://www.aemo.com.au/Media-Centre/2017-WA-Gas-Statement-of-Opportunities.

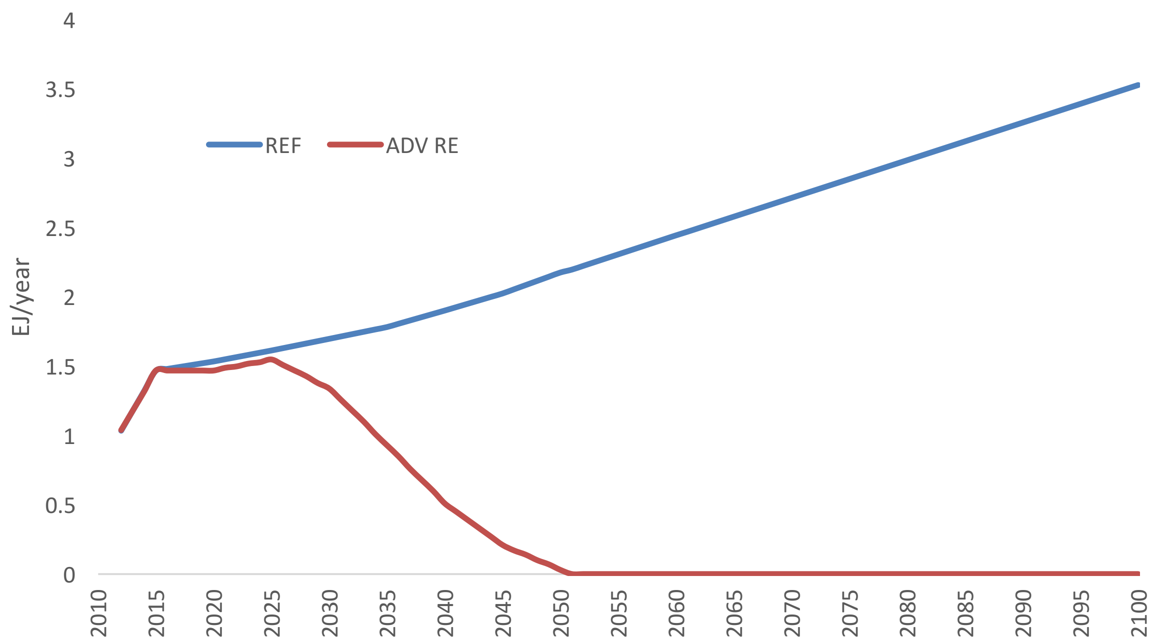


Figure 10: Natural gas demand pathways for Australia for a reference scenario without climate policy (REF) and a scenario compatible with the Paris Agreement (ADV RE). Source: Teske et al. (2016); own calculations: values for scenario REF after 2050 are extrapolated using Microsoft Excels TREND function.

HOW MUCH GAS DOES WESTERN AUSTRALIA NEED?

While natural gas will continue to play a role in a transition period, demand for gas in a Paris Agreement-compatible transformational pathway towards 100% renewable energy would start declining by or before 2030 and decrease to about zero before 2050.

We calculated the demand for gas for Western Australia based on the scenario shown above, downscaling it to Western Australia. We estimate a volume of 9.6 EJ would be needed between 2018 and 2050 for domestic use excluding LNG processing in Western Australia, that is, mostly for electricity supply and industry, including minerals processing and mining (see section on data and methodology for further details). After 2040, this demand is largely replaced by renewable energy alternatives readily available particularly in Western Australia. This estimated limited volume of natural gas needed in Western Australia until 2040 could be supplied just with the remaining gas reserves linked to existing production facilities in Western Australia (6.8 EJ), even if no new (conventional) gas fields were developed for the domestic market to replace depleted fields. Neither AEMO (2016) nor the more recent (AEMO 2017) projections take into account a transition towards a Paris Agreement compatible pathway with diminishing gas demand from the mid 2020s.

In any case, this limited future domestic demand can be met without any need to explore unconventional gas resources. There is no need to invest in gas transport infrastructure, given gas demand in all parts of Western Australia would be replaced by renewable energy options. In Australia as a whole only about half of gas existing reserves or less are needed (McGlade & Ekins 2015). The likely higher extraction cost for unconventional compared to conventional gas (McGlade & Ekins 2015) puts a question mark over any investment into infrastructure for transporting additional unconventional gas to other parts of Australia, such as a west-east pipeline.

THE CARBON FOOTPRINT OF WA GAS RESOURCES

Given the large scale of gas resources in Western Australia conventional gas reserves and resources (113,786 Petajoules (PJ)) and 222,057-330,223 PJ of unconventional reserves and resources (some tight and mostly shale gas) (Government of Western Australia 2017a) (see Table 5), their carbon footprint is relevant both internationally as well as domestically.

Table 5: Conventional and unconventional gas resources in Western Australia. Source: Government of Western Australia (2017a)

Basin	Amount of gas (PJ)		
	Conventional	Unconventional	
		Low	High
Bonaparte	17,709.4	0	
Browse	37,857.9	0	
Canning	1,590.7	152,704	237,540
Carnarvon	55,249.2	38,600	43,902
Perth	1,378.6	30,753	48,780
Total	**113,785.8**	**222,057**	**330,223**

Note: We use the conversion factor given in AEMO (2017, p.73) *to convert tcf to PJ: 1 tcf = 1000 bcf; 1000 bcf ≅ 1000 * 0.943 PJ.*

There are two main perspectives from which to view the carbon footprint of the WA's gas resources: global and domestic.

From the global perspective it is most relevant to look at the total potential release of carbon into the atmosphere, in the form of either carbon dioxide or methane, or a combination of both. The specific components of natural gas extraction activity which release carbon, for example within Australia, are not relevant. What is important for this assessment is the total volume of carbon in the resources and what fraction is likely to be released into the atmosphere as methane, in order to estimate the total global warming contribution if all resources. We adopt a carbon budget approach (Meinshausen et al. 2009) as this gives a scientifically robust yet relatively simple way of comparing the total available carbon in WA's natural gas resources with the amount of carbon that can be emitted for a given level of global warming.

Global carbon budget estimates for fossil fuel-related emissions are shown below in Table 6 for both the Paris Agreement 1.5°C limit and the former 2°C goal. In this analysis we have chosen to focus on the budget until 2050 as by this time in most scenarios fossil fuel emissions are close to zero. After 2050 there will be a need for negative emissions, hence budgets are negative for the 2051-2100 period. Unlike total global carbon budgets including land-use changes, budgets specifically for fossil-fuel related emissions are not readily available from international assessments such as IPCC's Fifth Assessment Report (IPCC 2014), or the UNEP Emissions Gap report series (e.g. (UNEP 2016; UNEP 2017)). The budgets in Table 6 were derived by re-analysis of the energy-economic modelling scenarios underlying those international assessments, as described in Rogelj et al. (2015), and represent carbon budgets from a typical scenario returning warming to 1.5°C by 2100, as a proxy for a Paris Agreement-compatible pathway, and from a typical scenario holding warming below 2°C with at least 66% probability throughout the 21st century. The budgets for these two warming limits were derived from a single energy-economic modelling framework to allow a like-with-like comparison.

Table 6 Cumulative global fossil-fuel related emissions ($GtCO_2$)

Warming limit	2015-2050	2018-2050	2051-2100	2015-2100
1.5°C	680	570	-300	380
2°C	930	820	-90	840

The second perspective estimates the Australia's domestic emissions arising from the development of these resources. Estimates of the greenhouse gas releases from different development scenarios, which exclude CO_2 and other GHGs released from combustion abroad, show how the industry affects domestics emissions profiles as reported to the UNFCCC and within the framework of the Paris Agreement. This involves estimating the emissions during all phases of extraction, processing, and domestic combustion, up to the point of export. These emissions can then be compared with, for example, Australia's Paris Agreement commitments and with its total CO_2 budget that would be consistent with the Paris Agreement.

GLOBAL CARBON FOOTPRINT OF WA GAS

The global carbon footprint of gas is estimated based on standard IPCC emission factors for natural gas. We assume that the reported energy content of the gas resources (PJ) is based on methane content and have therefore used a standard emission factor of 56.1 tCO_2 per TJ of natural gas[17]. When such a resource is developed, there will be a range of emissions from different activities across the whole supply chain, some of which involve releases from the gas reservoir, or other part of the supply, processing and transport chains, in the form of methane leakage, or release of CO_2 that is naturally stored in the gas reservoir. In addition, when gas is combusted there occur releases of methane and N_2O, as well as other air pollutants. At the point of combustion, CH4 releases are small (ca 0.04%)[17]. For the purposes of these global estimates we have not applied N_2O release factors, as these are quite small in GWP terms (0.05%)[17] compared to the CO_2 content.

For a global analysis of the CO_2 footprint of the development of a resource we need to estimate:

- Release of naturally occurring CO_2 in the reservoir to the atmosphere at any point in the supply and use chain.
- Losses of methane at any point in the supply and use chain. Every tonne of methane emitted, rather than fully combusted, will have a much larger warming effect than a tonne of methane converted to CO_2.
- Additional fossil fuels used in the development and transport of natural gas and its products. This latter component will not be evaluated here as it beyond the scope of this work.

17 We have applied IPCC emission factor with estimates uncertainty of +/-4%. See table 2.2 at http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf. Note that the natural gas emission factor used in the Australian GHG inventory is significantly lower at 51.4 tCO2/TJ in Table 3.2 Emission factors for CO2 2015 in Department of the Environment and Energy of the Australian Government, 2017. National Inventory Report 2015 Volume 1, Available at: http://www.environment.gov.au/climate-change/climate-science-data/greenhouse-gas-measurement/publications/national-inventory-report-2015. This emission factor is sourced to a series of gas industry publications in the 1990s to 2001 and pre-dates the IPCC 2006 guidelines and diverged substantially from other international estimates.

Naturally occurring CO_2 in gas reservoirs

WA gas fields contain significant fractions of naturally occurring CO_2. WA EPA reports on different natural gas projects provide some insight into the CO_2 content of currently operating (conventional) gas fields. There appears to be large range and some uncertainty across different gas fields in relation to the fraction[18] of naturally occurring CO_2 from these basins. For example, in 2007 the WA EPA indicated that the fraction from the Gorgon field could be as high as 14% (EPA 2007, p.22), whereas other fields are close to 2% (Table 7). We have estimated across the LNG fields a production weighted average of 7.2-7.7%, with significant uncertainty. Taking into account the requirement on Gorgon to capture and store a large fraction of reservoir $CO_{2,}$ and that domestic gas reservoirs may have CO_2 content of around 2%, a conservative estimate of reservoir CO_2 content is about 3.5%. Lack of available data does not permit a better estimate at this time. We have no basis for distinguishing between conventional and unconventional resources.

For the purposes of this work we assume a natural CO_2 fraction of about 3.5% of the gas in WA gas reservoirs. We note that if CCS CO_2 capture at Gorgon is not operationalised the average could increase to 7.2-7.7%.

[18] The fraction of naturally occurring CO_2 is estimated against the total carbon estimated to be emitted in production and ultimate combustion from each of the projects.

Table 7 Estimates of naturally occurring CO_2 at WA natural gas facilities

Facility	AEOMO 2017 Lowest in period 2018-2027	AEOMO 2017 Highest in period 2018-2027	Estimated reservoir CO2 content
	Nominal LNG production capacity (mtpa)	Nominal LNG production capacity (mtpa)	
Gorgon	15.6	20.8	14.0%[19]
North West Shelf	16.9	16.9	2.5%[19]
Pluto	5.3	5.3	2.0%[19]
Prelude Floating LNG (FLNG)	3.6	3.6	9.0%[20]
Wheatstone	13.3	17.8	3.0%[21]
Icyhthys (Browse Basin)	8.9	13.3	12.8%[22]
Total	**63.7**	**77.8**	**Production weighted average 7.2-7.7%**

Sources: Nominal production capacity inferred from Table 10 in AEMO (2016a) and sources for estimated reservoir CO_2 content are given in the footnotes. The production weighted average reservoir CO_2 content from reservoirs used for LNG production, before abatement is estimated here as *7.2-7.7%*. With 80% abatement reservoir CO_2 in the form of CCS at Gorgon required the production weighted average reservoir CO_2 release would reduce to about 3.8%. Taking into account domestic gas from reservoirs with CO_2 content of 2%, a conservative reservoir CO_2 content is about 3.5% is used in this work. Note that if CCS is not undertaken at scale at the Gorgon facility this rate would double.

Methane loss and leakage

Because methane is a much more potent greenhouse gas than CO_2, the rate of leakage of methane from production of natural gas largely determines the additional carbon footprint of natural gas over its lifecycle, compared to the footprint from its use for heating, electricity or industry energy conversion. Methane has 100 year Global Warming Potential (GWP)[23] of 25 (34), meaning that every tonne of methane (CH_4) emitted has a global warming effect of 25 (34) times that of one tonne of CO_2 measured over a period of one hundred years - we apply as a default the CH_4 GWP value of 25 adopted by the UNFCCC based on the 2007 IPCC Fourth Assessment Report, but show in parentheses the most recent 2013 IPCC Fifth Assessment Report value of 34.

Current greenhouse gas inventory estimates for fugitive emissions in Australia assume a much lower leakage rate of 0.48% (without venting or flaring) and 0.59% (with venting and flaring) (see Scientific

---

19 Page 22 of EPA, 2007. Pluto LNG Development , Burrup Peninsula. Report and recommendations of the Environmental Protection Authority, Perth, Western Australia. Available at: http://www.epa.wa.gov.au/sites/default/files/EPA_Report/2533_Bull1259.pdf.

20 Page 45, 47 of Shell Australia Pty Ltd, 2017. Prelude FLNG Environment Plan Summary Reviewed by, Available at: https://www.nopsema.gov.au/assets/epdocuments/A535000.pdf

21 Estimate made using data in Table 4.2 of Chevron, 2010. Draft Environmental Impact Statement/Environmental Review and Management Programme for the Proposed Wheatstone Project, Available at: http://www.epa.wa.gov.au/sites/default/files/PER_documentation/wheatstone_draft_eis_ermp_volume_i_%28chapters_1_to_6%298F72DBF90E8D.pdf

22 Average of CO_2 content of two reservoirs to be used for this project. See page 9 Gaffney, C.& A., 2008. Browse Basin Gas Technical Report Development Options Study Report 2 Of 3 Development Concepts For Development Of Browse Basin Gas, Available at: http://www.jtsi.wa.gov.au/docs/default-source/default-document-library/browse_site_selection_appendix_1_gaffney_cline_and_associates_report_2_0508.pdf?sfvrsn=12

23 https://en.wikipedia.org/wiki/Global_warming_potential

Inquiry into Hydraulic Fracturing in the Northern Territory (2017)) than current international estimates. The Northern Territory Inquiry has expressed concern that present inventory estimates appear too low, stating "These values underestimate field based measurements, which range from 1.6 - 1.9%. Further research is required to better understand the differences between these inventory and field based estimates". The International Energy Agency estimate a global average methane leakage rate of 1.7% (IEA 2017c, p.417). The IEA estimates do not take into account the possibility for higher leakage rates as discussed in many estimates of life cycle emissions from unconventional gas resources and also does not account for leakage of CO_2 and other GHGs contained in the natural gas to varying degrees. There are few if any estimates of leakage and loss rates from WA natural gas production. Emissions estimates from the production of unconventional gas resources via hydraulic fracking are very uncertain and heavily debated (see for example an overview given by Lafleur et al. (2016) with leakage rates between 2 and 17%), and there is a lack of data and analysis in Australia, which is why many studies rely on data and research about US shale gas production. These factors give rise to concern that actual fugitive emissions could be much higher than estimated in present Australia inventories.

For this work we assume a base methane loss rate for **conventional gas resources of 1.7%, while also showing the effects of a low 0.5% rate and high rate of 3%.** For unconventional resources where loss rates can be expected to be higher we have used a base rate of 6.5%, a low rate of 1.7% and a high rate of 17%, to account for the higher leakage rates discussed in many estimates of life cycle emissions from unconventional gas resources.

WA gas compared to global carbon budget

Total conventional gas resources in Western Australia amount to an estimated 113,786 PJ, which translates to about 2,321 $MtCH_4$ in the reservoirs that make up these resources.

If there were no methane losses at any stage in the development of these resources, and if there was no naturally occurring CO_2, then about 6,615 $MtCO_2$ would result from burning this resource. When released to the atmosphere this would amount to about 1.2% of remaining 1.5°C global carbon budget to 2050 (Table 8). Taking into account loss rates and naturally occurring CO_2 releases we estimate that development of all WA's conventional gas resources would release CO_2 emissions equivalent to about 1.3% (1.2-1.4%) of the same global carbon budget for 2018-2050.

Table 8 Conventional reserves and resources: Likely Total CO_2 equivalent emissions if all developed compared to global carbon budget

Scenario	Methane loss	Naturally occurring CO_2	$MtCO_2$ in resource including naturally occurring CO_2	$MtCO_2e$ emitted	Fraction of 1.5°C 2018-2050 budget	Fraction of 2°C 2018-2050 budget
Zero losses	0.00%	0.00%	6,615	6,615	1.16%	0.81%
Low	0.50%	3.50%	6,615	6,873	1.2%	0.8%
Base case	1.70%	3.50%	6,615	7,493	1.3%	0.9%
High	3.00%	3.50%	6,615	8,164	1.4%	1.0%

Total unconventional gas resources in Western Australia amount to between 222,057 and 330,223 PJ, which translates to between 4,530 and 6,736 $MtCH_4$ in the reservoirs that make up these resources. If there were no methane losses at any stage in the development of these resources, and if there were no naturally occurring CO_2, then about 12,909 to 19,197 $MtCO_2$ would result from burning this resource (Table 9). When released to the atmosphere this would amount to about 2.3 to 3.4% of the remaining 1.5°C global carbon budget to 2050.

Taking into account loss rates and naturally occurring CO_2 releases we estimate that development of all WA's unconventional gas resources would release CO_2 emissions equivalent to about 3.4-5.1% of the global carbon budget to 2050 for base case estimates of CO_2 content and CH_4 losses and low and high resource estimates (full range with low and high leakage rate estimates: 2.6%-7.8%).

Table 9: Unconventional resources: Likely Total CO_2 equivalent emissions if all resources developed compared to global carbon budget

Scenario	CH_4 loss rate	Naturally occurring CO_2	$MtCO_2$ in resource including naturally occurring CO2		$MtCO_2e$ emitted		Fraction of 1.5°C 2018-2050 budget		Fraction of 2°C 2018-2050 budget	
			Low	High	Low	High	Low	High	Low	High
Zero losses	0.0%	0.00%	12,909	19,197	12,909	19,197	2.3%	3.4%	1.6%	2.3%
Low	1.7%	3.50%			14,623	21,745	2.6%	3.8%	1.8%	2.6%
Base	6.5%				19,461	28,940	3.4%	5.1%	2.4%	3.5%
Highest	17.0%				30,044	44,678	5.3%	7.8%	3.7%	5.4%

The total carbon equivalent of conventional and unconventional gas resources in Western Australia adds up to a surprisingly high fraction of 3.8-9.2% of a 1.5°C global carbon budget to 2050 (2.6%-6.4% of a 2°C carbon budget) (

Table 10). Based on the average leakage factor of 1.7% estimated by the (IEA 2017c) for conventional and 6.5% for unconventional (Bista et al. 2017), and assuming naturally occurring CO_2 fraction of around 3.5%, the overall greenhouse gas footprint of all of the Western Australian gas resources, if they were all to be extracted and used, is estimated to be about 30.0-36.4 $GtCO_2$ equivalent emissions (7.5 $GtCO_2e$ from conventional resources, and 19.5-28.9 $GtCO_2e$ from unconventional resources). This footprint estimate is dominated by the emissions from burning of natural gas. Even if the leakage rate would be lowered considerably (0.5% for conventional and 1.7% for unconventional), the footprint would be about 21.5-28.6 $GtCO_2$ equivalent emissions. This corresponds to between 3.8-5% of the total global carbon emissions budget between 2018 and 2050 in a Paris Agreement consistent pathway and is therefore relevant internationally (Table 10). If we assume the extreme case of 17% leakage from unconventional resources, the top end of the range of estimates shown in Lafleur et al. (2016b), and 3% leakage for conventional gas the emissions budget would increase to 52.5 Gt, or about 9% of the global budget.

Table 10 Carbon footprint of total gas reserves and resources compared to Paris Agreement global carbon budget

Scenarios	Fraction of 1.5°C 2018-2050 budget		Fraction of 2°C 2018-2050 budget	
	Low	High	Low	High
Zero losses	3.4%	4.6%	2.4%	3.1%
Low	3.8%	5.0%	2.6%	3.4%
Base	4.7%	6.5%	3.3%	4.4%
High	5.7%	9.2%	4.7%	6.4%

Notes: *Low* refers to 0.5% methane loss in conventional and 1.7% in unconventional reserves and resources, *Base* refers to 1.7% methane loss in conventional and 6.5% in unconventional reserves and *High* refers to refers to 3% methane loss in conventional and 17% in unconventional reserves.

Looking just at the Canning Basin unconventional resources, which amount to between 69-72% of the energy content of this class of gas resources in Western Australia, there is a surprisingly large amount of carbon, which would have a significant impact on the global carbon budget. Applying our low case scenario of 1.7% leakage rate of methane over the entire extraction and use cycle, along with the estimate of 3.5% naturally occurring CO_2 *in situ* this basin would account for about 1.8-2.7% of the 2018 to 2050 1.5°C Paris Agreement carbon budget. With higher methane leakage rates, which indeed seem likely from unconventional resource extraction at the 6.5% loss rate estimated by Bista et al. (2017) this would correspond to about 2.2-3.7% of the global budget. The highest level of leakage in the literature of 17% would account for 3.6-5.6% of this common global budget.

IMPACT ON WEST AUSTRALIAN AND AUSTRALIAN CARBON EMISSIONS AND BUDGET

The relevance of the carbon footprint in the national or Western Australian context is best assessed by looking at the domestic part of the footprint, that is, the share of the emissions that would actually occur in Australia/Western Australia. This depends on the assumption about what happens with the gas – whether it is used in Australia or whether it is exported. However, the direct (upstream) emissions from the production process, in particular the related fugitive emissions, would occur in Western Australia in any case. Combustion within Australia/Western Australia for power or heating (also referred to as "downstream"), as well as additional emissions occurring during production and transport (also referred to as "upstream"), mostly due to leakage (fugitive emissions) of methane and CO_2, will also appear on the national emission accounts.

WA and Australian Carbon Budget

The overall cumulative energy sector CO_2 emissions in Australia in a Paris Agreement compatible pathway estimated as the cumulative energy related emissions in the 100% renewable scenario described above, between 2018 and 2050 (Teske et al. 2016), for the period 2018-2050 is about 5.5 $GtCO_2$. If we assume the same share of emissions for Western Australia as at present (18%), the budget for Western Australia would be 988 Mt, or in round terms about 1 $GtCO_2$. Regardless of whether the gas is exported or used in Australia, the fugitive emissions resulting from the extraction and cleaning of the gas including from venting and flaring would take place in Western Australia.

Domestic emissions footprint

The domestic carbon footprint from production of all gas reserves and resources in Western Australia depends on what happens with the gas once it is produced: whether it is used in Australia or exported. It is most likely that it would be partly used domestically, as is being discussed for the Canning Basin resources, and partly exported as LNG, as most of the gas produced in Australia today.

Below we estimate the domestic carbon footprint from upstream emissions from extraction and production of all of Western Australia's conventional and unconventional remaining gas resources, direct combustion and/or use in LNG processing, and compare this to the overall cumulative remaining emissions budget for the Western Australian and Australian energy sectors in a pathway consistent with the Paris Agreement, drawing from the scenarios outlined in the previous sections. In addition to the usual categories for upstream emisssions we have included CO_2 content of the resources. As outlined above in our calculations we have used a CO_2 content rate of 3.5% (Mole fraction of gas in resource) as a conservative estimate. We place this source of emissions in the upstream/direct category as any CO_2 emissions will occur within Western Australia and hence in the Australian National greenhouse gas accounts.

To estimate the carbon footprint, all relevant emissions sources "from cradle to grave" (Bista et al. 2017) need to be taken into account in a Life Cycle Analysis (LCA): emissions occurring during the production process, including LNG processing, given the importance of LNG exports in Australia and Western Australia, as well as emissions occurring during transport and consumption/end use. Due to the difference in the gas extraction process, fugitive emissions during extraction, for example due to faulty seals or leaking valves, faulty designs of the facility or equipment, are generally higher for unconventional gas resources. The extent of these fugitive emissions depends on controls and regulations. To compute the emissions resulting from extraction and processing (cleaning of the gas), we used the approaches outlined in Hardisty et al. (2012) for conventional and Bista et al. (2017) for unconventional gas. Upstream emissions as estimated by Hardisty et al. (2012) for conventional gas seem to be quite conservative, with an effective leakage rate of 0.13%.

For the domestic carbon footprint**,** we estimate the share of emissions from development of resources that would actually occur in Australia/Western Australia. Gas that is used abroad as LNG is not recorded as an emission in Australia nor are the associated shipping emissions or regasification emissions. Direct (upstream) emissions of CO_2 and methane from the exploration and production process, in particular the related fugitive emissions, would occur in Western Australia under any use scenario, even though the pathways to release may be different depending on whether gas is used domestically or for LNG export. Combustion within Australia/Western Australia for power or heating, or in the LNG processing also appears on the national emission accounts.

When used domestically, the largest part of the carbon footprint results from using gas for electricity, heating or industry, in addition to the production footprint. When exported, emissions from LNG processing have to be accounted for in addition to the production emissions. Domestically used gas is assumed to be burned to CO_2 without further CH_4 emissions to provide power, heat and as feedstock in the chemical industry. The exported part needs to be liquefied for export, a process that uses about 8-9% of the gas for energy (resulting in CO_2 emissions) and also resulting in further leakage. Both the CO_2 and CH_4 emissions from LNG processing need to be taken into account as occurring domestically in Western Australia.

Greenhouse gas emissions that would occur in Western Australia (and of course Australia) from use of all the presently estimated conventional reserves and resources – upstream emissions, CO_2 in the gas stream, domestic use, and LNG processing emissions – are estimated to be in the range of 1.43-1.75 $GtCO_2e$ (about 19 to 23 % of the global carbon footprint). WA domestic emissions differ a little depending on the balance of domestic use and LNG export, which can be seen in Table 11[24]. A business as usual scenario based on the 2017 AEMO projections extended to 2050 indicates total domestic use emissions[25] at about 0.93 $GtCO_2e$ and LNG related emissions[26] to be about 0.81 $GtCO_2e$. In other words, up to 2050 and under present policies the domestic use related emissions from the use of all presently estimated conventional resources are about equivalent to the entire Paris Agreement carbon budget for WA (about 1 $GtCO_2$) before considering LNG related emissions.

Upstream) emissions from conventional reserves add up to a total of 0.3 Gt CO_2e (see Table 11 below)– with higher CH_4 leakage rates at the IEA level assumed above this would be about 1.2 $GtCO_2e$. This is between about 30% and 1720% of the emissions budget for energy related CO_2 emissions for the transition of Western Australia to zero emissions (calculated to be about 1$GtCO_2$ (988 Mt CO_2), see above). At present rates of usage projected for the 2020s, both domestic and LNG export, the present conventional natural resource would have a lifetime of about 30 to 35 years. As shown above, by the end of this time the world would need to be close to zero fossil fuel CO_2 emissions at the Paris Agreement goals are to be met.

The full exploitation of presently estimated conventional reserves and resources to fulfil business as usual domestic WA demand and with LNG exports maintained at maximum projected capacity to the mid 2040s would result in domestic Western Australian GHG emissions about 75% above the estimated Paris Agreement budget for WA.

Table 11 Scenarios for conventional resource domestic carbon gas footprint

	AEMO 2017 Base case WA domestic gas demand projection to 2027 extended to 2050		Paris Agreement scenario WA domestic gas demand	
WA gas pool PJ	113,786	PJ	113,786	PJ
WA Domestic use PJ 2018-2050	15,820	PJ	9,564	PJ
WA Domestic use combustion emissions	887	$MtCO_2e$	537	$MtCO_2e$
Upstream emissions from WA domestic gas use	41	$MtCO_2e$	25	$MtCO_2e$
Export use for LNG processing and export	97,966	PJ	104,222	PJ
LNG processing emissions (not including CO_2 in gas stream)	562	$MtCO_2e$	598	$MtCO_2e$
Upstream emissions associated with LNG production	255	$MtCO_2e$	271	$MtCO_2e$
Total domestic emissions in WA	1,746	$MtCO_2e$	1,430	$MtCO_2e$
Fraction of WA energy system carbon budget (1 Gt CO_2)	1.75		1.43	

[24] Assuming WA conventional gas does not enter the eastern Australian domestic gas market, which could result in lower LNG exports.

[25] WA Domestic use combustion emissions + Upstream emissions from WA domestic gas use, see Table 2

[26] LNG processing emissions (not including CO2 in gas stream) + Upstream emissions associated with LNG production, see Table 2

The projected domestic use of the conventional resources amounts to an annual average of about 4.8% of 2005 Australian GHG emissions[27], the LNG related emissions about 5.5% in the period to 2050. The fraction of WA emissions is much higher, 40% of WA 2005 GHG emissions from domestic gas use and 45% from LNG related emissions.

While the complete exploitation of conventional gas resources is clearly problematic without massive mitigation measures compared to the emission reduction required for the Paris Agreement, the scale of unconventional resources is in another class. There are massive amounts of methane and carbon stored in unconventional resources, mainly in the Canning Basin. We use a stylised scenario to illustrate this, with half of Australia's projected business as usual natural gas demand until 2100 assumed to be met from Canning Basin, via a west-east pipeline (for which pre-feasibility work is underway at present), with the remainder exported as LNG.

Total Australian domestic emissions from the complete use of unconventional resources could amount to 10.0-18.5 GtCO_2e, equivalent to 17-31 years of 2005 Australia GHG or 1.8-3.4 times the entire Paris Agreement compatible carbon budget for Australia. Upstream emissions would be a large part of this. With the CH_4 loss rates estimated by Bista et al. (2017), the range of recent resource estimates and a plausible utilisation scenario about 7.8-11.8 GtCO_2e (see Table 12 below) could be released from the complete utilisation of the presently estimated unconventional gas resources.. Halving upstream emissions with optimistic assumptions about reduced leakage and loss rates for hydraulic fracturing (fracking), and assuming that flaring and venting emissions could be avoided, would still leave large upstream emissions (4.0-5.9 GtCO_2e comparable to the Paris Agreement compatible CO_2 emissions budget for Australia's total energy system (about 5.5 GtCO_2). This footprint with optimistic assumptions for halving upstream emissions - managing fugitive emissions and avoiding venting and flaring emissions - from unconventional gas production is still 4-5 as high as the total emissions budget estimated for the energy sector for Western Australia. Emissions from direct use of gas would amount to about 5.3 GtCO_2e and LNG processing emissions to about 0.7-1.3 GtCO_2e.

[27] UNFCCC inventory of 597.4 MtCO2e in 2005 (including LULUCF) http://ageis.climatechange.gov.au/UNFCCC.aspx

Table 12 Illustrative scenarios for unconventional resource use domestic carbon footprint

	Standard upstream emissions and losses case			50% reduction in upstream emissions and losses		
	Low resources	High resources	Unit	Low resources	High resources	Unit
WA Unconventional resource	222,057	330,223	PJ	222,057	330,223	PJ
50% of projected total a domestic Australian gas use scenario to 2100	95,142	95,142	PJ	95,142	95,142	PJ
Domestic use combustion emissions	5,337	5,337	MtCO2e	5,337	5,337	MtCO2e
Upstream emissions from domestic gas use	3,412	3,412	MtCO2e	1,706	1,706	MtCO2e
Total emissions from domestic gas use	**8749**	**8749**	**MtCO2e**	**5043**	**5043**	**MtCO2e**
Export use for LNG processing and export	126,915	235,080	PJ	126,915	235,080	PJ
LNG processing emissions (not including CO2 in gas stream)	728	1,349	MtCO2e	728	1,349	MtCO2e
Upstream emissions associated with LNG production	4,552	8,431	MtCO2e	2,276	4,216	MtCO2e
LNG export gas production and processing related emissions	**5,280**	**9,780**	**$MtCO_2e$**	**3,004**	**5,564**	**$MtCO_2e$**
Total Australian domestic emissions	**14,030**	**18,530**	**MtCO2e**	**10,048**	**12,608**	**MtCO2e**
Total WA Emissions	**9,111**	**13,611**	**MtCO2e**	**3,004**	**5,564**	**MtCO2e**

Notes: Domestic Australian use scenario is a hypothetical to illustrate the carbon footprint of large scale use of unconventional resources to supply a large fraction (50%) of one plausible Australian gas demand scenario to 2100 used in the body of this report. The WA emissions footprint for this hypothetical scenario assumes all LNG processing is in WA, and about 45% of the approximate 95,000 PJ of Australian demand in this scenario is in WA.

Putting these results together shows quite clearly that using all conventional and unconventional resources is fully inconsistent with climate protection goals, and in particular with a reasonable carbon budget for Australia or Western Australia. Table 13 below shows the results for both conventional and unconventional reserve and resource use illustrative scenarios.

To estimate the domestic emissions occurring in Australia from all the Western Australian gas reserves and resources, we look at two different scenarios for domestic gas demand and therefore for the share of domestic use and export use of the remaining gas (after taking into account the losses due to upstream emissions). Based on the REF scenario described above, 42-56% of the total gas reserves and resources would be used in Australia, whereas the remainder could be used for the processing and exported of LNG. For the ADV RE scenario, only a 7-9% share would be used domestically and the rest could be exported if all were to be used.

In the REF scenario total domestic emissions would be 19.8-24.3 GtCO_2e (see Table 13) based on the Bista et al. (2017) estimates for fugitive emissions and Hardisty et al. (2012) estimates for LNG processing emissions, and assuming the whole volume of gas would be extracted and used (partly exported), and no climate policy would be implemented ("business as usual"). This would exceed the emissions budget in Australia's energy sector more than fourfold and by far exceed the emissions budget in Western Australia and therefore totally undermine the Paris Agreement temperature goal and Western Australia's ability to contribute to achieving it.

Under the reference scenario – business as usual domestic Australian gas use and LNG exports – could result in domestic Australian emissions of around 19.8-24.3 GtCO_2e, about four times the Paris Agreement Australian budget (5.5 GtCO_2) assumed here. Western Australian emissions in the reference scenario for both conventional and unconventional resources would be about 7.8-11.9 GtCO_2e assuming all WA domestic gas is sourced from these resources and all LNG processing from these resources takes place in WA. In round terms this would be some 8-12 times higher than a reasonable Paris Agreement budget for WA.

In an illustrative scenario where Australia moves to meet the Paris agreement goals, the overall domestic carbon footprint of the total use of these resources and reserves is lower than in the reference case, given more would be assumed to be exported. However, there remain very large emissions associated with LNG processing and with associated upstream emissions from gas production, which substantially exceed a reasonable carbon budget for Australia under the Paris Agreement. In this case, because of the larger amount of the assumed LNG processing in Western Australia, compared to the reference case, Western Australia emissions are higher in total than in the reference case.

Table 13 Illustrative Scenarios for conventional and unconventional reserve and resources carbon footprint

Conventional and unconventional resource scenarios	Units	Reference scenario		Paris Agreement pathway	
		Low resources	High resources	Low resources	High resources
WA gas resources	PJ	335,843	444,008	335,843	444,008
Domestic use scenario to 2100 (Australia)	PJ	190,285	190,285	30,301	30,301
Domestic use combustion emissions	Mt CO_2e	10,675	10,675	1,700	1,700
Upstream emissions from domestic gas use		4,680	5,203	745	828
Export use for LNG processing and export	PJ	145,558	253,724	305,543	413,708
LNG processing emissions (not including CO2 in gas stream)	Mt CO_2e	835	1,456	1,753	2,373
Upstream emissions associated with LNG production	Mt CO_2e	3,580	6,937	7,515	11,311
Total domestic Australian emissions	**Mt CO_2e**	**19,770**	**24,270**	**11,713**	**16,213**
Total WA domestic emissions	**Mt CO_2e**	**7,777**	**11,869**	**10,040**	**14,483**

Notes: The emission results are based in the scenarios shown in Tables 2 and 3 above. Domestic Australian use scenario is a hypothetical to illustrate the carbon footprint of large scale use to supply a large fraction (100%) of one plausible Australian gas demand scenario to 2100 used in the body of this report. The WA emissions footprint for this hypothetical scenario assumes all LNG processing is in WA. Note that the WA component of emissions in this scenario is less than in the Illustrative scenarios for unconventional resource use only (Table 12) as in this scenario WA demand is satisfied first from conventional reserves and resources which have lower assumed CH_4 loss rates.

Even if WA and Australia would reduce its domestic use of natural gas to be in line with a Paris Agreement compatible scenario (ADV RE), the resulting upstream emissions from LNG exports would be more than twice the carbon budget for the whole of a Paris Agreement compatible budget for the entire Australian energy system. While domestic use emissions are much smaller in the ADV RE scenario, the overall emissions related to Western Australia's gas resources do not shrink that significantly, since upstream emissions stay the same and LNG processing emissions get even bigger since more gas (about 90-93% in ADV RE vs. 43-57% in REF) is used for LNG processing and export. With lower domestic demand, the share of export is higher for the same volume of gas resources used and hence higher LNG processing emissions (and same upstream emissions). Assuming the reduced domestic gas demand calculated in the advanced renewable energy scenario towards 100% renewable energy, and reduced leakage rates for unconventional gas, this would still amount to a total of domestic emissions of about 11.7-16.2 GtCO2e, with 1.8-2.3 Gt from LNG processing, 7.5-11.3 GtCO2e from upstream emissions associated with LNG production, 1.7 GtCO2 from domestic use, 0.7-0.83 from upstream emissions associated with domestic use. In these estimates around 8-12 GtCO2e come from upstream emissions, including fugitive emissions, from unconventional gas production. Even if only half of these unconventional gas resources would be extracted (and mostly exported), this would result in domestic emissions of 5.1 Gt CO_2eq, almost the total emissions budget for Australia's entire energy sector.

OPPORTUNITY FOR WA TO TRANSITION FROM A GAS EXPORTER TO A RENEWABLE ENERGY SUPERPOWER

Overall, it can be concluded that production of unconventional gas would leave hardly any or no space for the necessary transition of electricity, transport and industry towards zero emissions, even with optimistic assumptions about reduced leakage rates. This shows how unsustainable the extraction and processing of these resources would be: exploitation of conventional, let alone unconventional resources is fundamentally inconsistent with the Paris Agreement, in terms of associated domestic emissions, even without the implications of end-use emissions abroad.

On the global scale, we have already shown that exploitation of additional resources is inconsistent with the Paris Agreement, given that only half of the existing proven reserves could be used, let alone any additional resources, and that a continuation of LNG export rates as projected risk investments into stranded assets, given the expected decline in global gas demand.

The Paris Agreement creates a major opportunity for Western Australia to transition towards becoming a renewable energy superpower in its own right. This will mean that investments and operations need to be transitioning away from fossil fuels to meet the Paris Agreement goals as well as benefit from the opportunities of such a transition. It is important to take a long-term perspective to ensure a transition avoiding disruptions, but also avoiding locking into carbon intensive infrastructure and thereby creating stranded assets.

Unlike coal, which must be phased out very quickly, gas plays an important but limited role in this transition, allowing some time to develop alternative renewable energy industries, infrastructure and markets. Over commitment and over investment in gas, as would be the case for the exploitation of the Canning Basin resources, would obstruct instead of facilitate the advantage of this once in a generation opportunity.

Recent international assessments indicate that implementation of the Paris Agreement is beginning to build momentum. For example the Climate Action Tracker, a scientific consortium of three institutions including Climate Analytics, has calculated for the first time since it began its international assessments in 2009, that the effects of climate policy in place and planned are likely to reduce projected global warming to 2100 (Climate Action Tracker 2017c). This reflects the build-up of renewable energy in India and China, the stagnation or even reduction in coal use in many parts of the world as well as a range of other developments.

While the outlook for gas demand in the mid to longer-term is not promising under the Paris Agreement, this does not mean that the economic outlook for Western Australia as a major resource exporter is under a cloud. Like in many regions, economic transformation is an essential element of a strategy focused on economic growth and renewal. The Paris Agreement offers immense opportunities to the region. Western Australia has very large and accessible renewable resources, notably solar, wind and geothermal, as well as mineral resources critical to the global low carbon transformation. Western Australia hosts the technical, engineering and logistical capacities to take advantage of these opportunities.

Apart from further development of mineral resources essential for the low carbon transition globally (World Bank 2017), two major branches of renewable energy exports to replace the gas industry in the mid-to long-term are under active discussion. These are (a) the production and export of renewable hydrogen, in one form or another, and (b) the export of renewable energy electricity directly to the rapidly growing Southeast Asian region, and in particular to Indonesia.

Renewable energy carriers such as hydrogen can be burnt in gas turbines to produce electricity, or directly involved with steel production. South Australia has, for example, invested about $150 million in scoping opportunities for hydrogen production systems (Dunis 2017). The Pilbara and northwest coastal regions of Western Australia have very high solar energy potential, as well as engineering and transport infrastructure and capacities, which could help to facilitate a transition from gas export to renewable hydrogen export over the next few decades.

In relation to direct electricity export, Indonesia is in fact very close to northern (Western) Australia and is a rapidly growing market confronting serious air pollution and energy resource development bottlenecks. Providing significant sub-sea engineering issues can be overcome, supplying renewable sourced electricity to this region could become a very important market in the next 20 years. In the Pilbara, on the back of a recent pre-feasibility study, support is now being sought from the Northern Australia Infrastructure Fund (NAIF) for initial work on solar photovoltaic capacity ultimately for export to Indonesia (REneweconomy 2017c; REneweconomy 2017b).

APPENDIX: NATURAL GAS IN AUSTRALIA: PRODUCTION, CONSUMPTION, AND RELATED GREENHOUSE GAS EMISSIONS

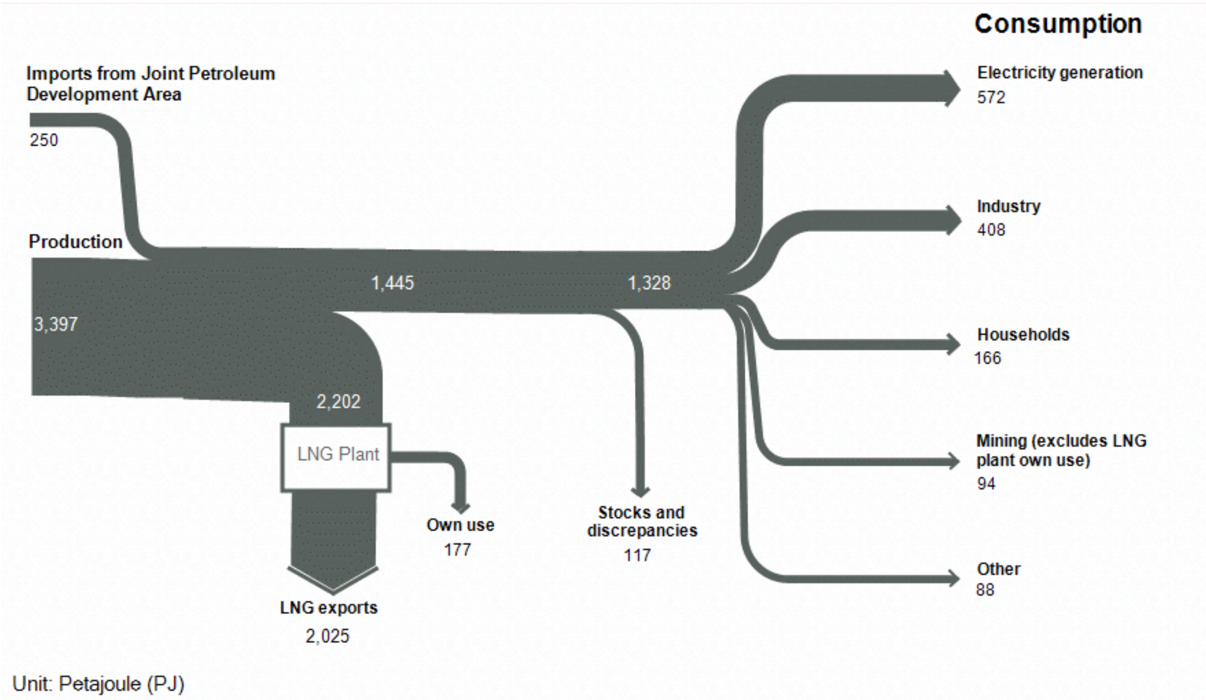


Figure 11: Natural gas flows Australia 2015-2016, Source: Commonwealth of Australia (2017)

With 1,505 PJ, natural gas accounted for 25 % of energy consumption in fiscal year 2015-16 in Australia. This implies a rise by 5 % compared to the previous year, due to increased gas use in Queensland to support the expansion of LNG exports. In LNG production, the plant consumes around 9 % of gas flows during the liquefaction process, with the remainder exported as LNG. LNG plants' own use accounted for approximately one-tenth of total Australian gas consumption in fiscal year 2015-16 (Commonwealth of Australia 2017b).

Greenhouse gas emissions in Australia from consumption of gas are mostly energy-related (including fugitive emissions) as well as, to a small extent, due to the use as feedstock for ammonia production (industrial process related emissions). Ammonia production is projected to stagnate, with increases in domestic demand for ammonia expected to be met by imports (Commonwealth of Australia 2016).

AUTHORS

Bill Hare, Niklas Roming, Ursula Fuentes Hutfilter, Michiel Schaeffer, Ela Smith, Matt Beer

ACKNOWLEDGEMENT

The authors thank Sangita Bista for contributing to early drafts and providing advice and review based on her work on life-cycle analysis of unconventional gas resources in Western-Australia. Thanks are also due to Fabio Sferra, Paola Parra, and Jasmin Cantzler for reviewing earlier versions, Ela Smith for editing of the report and Matt Beer for data visualisation, graphic design and layout.

REFERENCES

ACOLA, 2017. *The Role of Energy Storage in Australia's Future Energy Supply Mix*, Available at: www.acola.org.au.

AEMO, 2017. *Gas Statement of Opportunites for Western Australia*, Available at: https://www.aemo.com.au/Media-Centre/2017-WA-Gas-Statement-of-Opportunities.

AEMO, 2016a. *Gas Statement of Opportunites for Western Australia*, Available at: http://www.aemo.com.au/-/media/Files/Gas/National_Planning_and_Forecasting/WA_GSOO/2016/2016-WA-Gas-Statement-of-Opportunities.pdf.

AEMO, 2016b. *National Gas Forecasting Report for Eastern and South-Eastern Australia*, Available at: https://www.aemo.com.au/-/media/Files/Gas/National_Planning_and_Forecasting/NGFR/2016/2016-National-Gas-Forecasting-Report-NGFR-Final.pdf.

APPEA, 2016. Natural gas will play a pivotal role in post Paris Agreement future. *Appea*, (November 2016), p.9426. Available at: https://www.appea.com.au/media_release/gas-pivotal-role-post-paris-agreement/ [Accessed November 6, 2017].

ARENA, 2015. *Renewable energy: Options for Australian Industrial Gas Users*, Available at: http://www.itpau.com.au/wp-content/uploads/2017/11/ITP_REOptionsForIndustrialGas_TechReport.compressed.pdf.

Australian Bureau of Statistics, 2016. Australian National Accounts: State Accounts, 2015-16. Available at: http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/5220.0Main+Features12015-16?OpenDocument [Accessed October 25, 2017].

Australian Government, 2017. *Australia' s emissions projections 2017*, Available at: http://www.environment.gov.au/system/files/resources/eb62f30f-3e0f-4bfa-bb7a-c87818160fcf/files/australia-emissions-projections-2017.pdf.

Australian Government, D. of the E. and E., 2017. National Greenhouse Gas Inventory - Kyoto Protocol classifications. *Australian Greenhouse Emissions Information System*. Available at: http://ageis.climatechange.gov.au [Accessed October 5, 2017].

Bista, S., Jennings, P. & Anda, M., 2017. Cradle to grave GHG emissions analysis of shale gas hydraulic fracking in Western Australia. *Renewable Energy and Environmental Sustainability*, 45, pp.1–8.

Blakers, A., Lu, B. & Stocks, M., 2017. 100 % renewable electricity in Australia. , (February).

BNEF, 2017. *Electric vehicle outlook 2017 - Executive Summary*, Available at: https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF_EVO_2017_ExecutiveSummary.pdf [accessed on 14 December 2017].

BZE, 2015. *Renewable Energy Superpower*, Available at: http://media.bze.org.au/resp/bze_superpower_plan.pdf.

BZE, 2017. *Rethinking Cement*, Available at: http://media.bze.org.au/ZCIndustry/bze-report-rethinking-cement-web.pdf.

BZE, 2016. *Zero Carbon Australia: Electric Vehicles*, Available at: http://bze.org.au/electric-vehicles-report/.

BZE, 2014. *Zero Carbon Australia: High Speed Rail*, Available at: http://bze.org.au/zero-carbon-transport-high-speed-rail.

Cassidy, N. & Kosev, M., 2015. *Australia and the Global LNG Market*, Available at: http://www.rba.gov.au/publications/bulletin/2015/mar/pdf/bu-0315-4.pdf.

CCA, 2014. *Reducing Australia's Greenhouse Gas Emissions - Targets and Progress Review*, Available at: http://climatechangeauthority.gov.au/../Targets and Progress Review Final Report.pdf.

Climate Action Tracker, 2017a. Australia. Available at: http://climateactiontracker.org/countries/australia.html [Accessed December 15, 2017].

Climate Action Tracker, 2017b. *Foot off the gas: increased reliance on natural gas in the power sector risks an emissions lock-in*, Available at: http://climateactiontracker.org/assets/publications/briefing_papers/CAT_20170616_DecarbonisationSeries_NaturalGas.pdf.

Climate Action Tracker, 2017c. *Improvement in warming outlook as India and China move ahead, but Paris Agreement gap still looms large*, Available at: http://climateactiontracker.org/assets/publications/briefing_papers/CAT_2017-11-15_Improvement-in-warming-outlook.pdf.

Climate Action Tracker, 2016. The ten most important short-term steps to limit warming to 1.5°C.

Climate Analytics, 2016. *Implications of the Paris Agreement for Coal Use in the Power Sector*, Berlin. Available at: http://climateanalytics.org/publications/2016/implications-of-the-paris-agreement-for-coal-use-in-the-power-sector.html.

Climate Analytics & UNDP, 2016. *Low Carbon Monitor 2016: Pursuing the 1.5C limit - Benefits and Opportunities*,

Climate Change Authority, 2016. *Policy options for Australia's electricity supply sector*,

Climate Council, 2017. *Renewables Ready: States Leading the Charge*, Available at: https://www.climatecouncil.org.au/uploads/9a3734e82574546679510bdc99d57847.pdf.

ClimateWorks Australia, 2014a. Pathways to Deep Decarbonisation in 2050: How Australia can proser in a low carbon world:Technical Report. , (May), p.1. Available at: http://www.climateworksaustralia.org/publications/reports-documents.

ClimateWorks Australia, 2014b. *Pathways to Deep Decarbonization in 2050 - How Australia Can Prosper in a Low Carbon World*, Available at: http://deepdecarbonization.org/wp-content/uploads/2015/09/AU_DDPP_Report_Final.pdf.

Commonwealth of Australia, 2017a. *2017 Review of Climate Change Policies*,

Commonwealth of Australia, 2016. *Australia's emissions projections 2016*, Available at: https://www.environment.gov.au/system/files/resources/9437fe27-64f4-4d16-b3f1-4e03c2f7b0d7/files/aust-emissions-projections-2016.pdf.

Commonwealth of Australia, 2017b. *Australian Energy Update 2017*, Available at: https://www.energy.gov.au/publications/australian-energy-update-2017.

Commonwealth of Australia, 2017c. *State and Territory Greenhouse Gas Inventory 2015*, Available at: http://passthrough.fw-notify.net/download/650369/http://www.environment.gov.au/system/files/resources/15d47b77-dee2-42c6-bf2e-6d73e661f99a/files/state-inventory-2015.pdf.

Creutzig, F. et al., 2017. The underestimated potential of solar energy to mitigate climate change. *Nature Energy*, 2. Available at: https://www.nature.com/articles/nenergy2017140.

Dunis, V., 2017. Could South Austrlia be the nation's hydrogen state, too? *RenewEconomy.com.au*. Available at: http://reneweconomy.com.au/could-south-australia-be-the-nations-hydrogen-state-too-11243/ [Accessed December 15, 2017].

ENA, 2017. *Electricity Network Transformation Roadmap: Final Report*,

EPA, 2007. *Pluto LNG Development, Burrup Peninsula*, Available at: http://www.epa.wa.gov.au/sites/default/files/EPA_Report/2533_Bull1259.pdf.

Geoscience Australia, 2016. Australian Energy Resource Assessment. Available at: http://www.ga.gov.au/aera [Accessed October 19, 2017].

Government of Western Australia, 2017a. *WA Liquefied Natural Gas Industry Profile*, Available at: http://www.jtsi.wa.gov.au/docs/default-source/default-document-library/wa-lng-profile-0917.pdf?sfvrsn=6.

Government of Western Australia, 2017b. Western Australia Economic Profile. , (September), pp.1–12.

Gulagi, A., Bogdanov, D. & Breyer, C., 2017. A Cost Optimized Fully Sustainable Power System for Southeast Asia and the Pacific Rim. *Energies*, 10(5), p.583. Available at: http://www.mdpi.com/1996-1073/10/5/583.

Haluszczak, L.O., Rose, A.W. & Kump, L.R., 2013. Applied Geochemistry Geochemical evaluation of flowback brine from Marcellus gas wells in. *Applied Geochemistry*, 28, pp.55–61. Available at: http://dx.doi.org/10.1016/j.apgeochem.2012.10.002.

Hardisty, P.E., Clark, T.S. & Hynes, R.G., 2012. Life Cycle Greenhouse Gas Emissions from Electricity Generation: A Comparative Analysis of Australian Energy Sources. *Energies*, 5, pp.872–897.

Hare, B. et al., 2016. *Implications of the 1.5°C limit in the Paris Agreement for climate policy*, Available at: http://climateanalytics.org/files/1p5_australia_report_ci.pdf.

Hare, B. et al., 2017. *The Finkel Review and scientific consistency with the Paris Agreement*, Available at: http://climateanalytics.org/publications/2017/the-finkel-review-and-scientific-consistency-with-the-paris-agreement.html.

IEA, 2017a. *Energy Technology Perspectives 2017*, Available at: http://www.iea.org/publications/freepublications/publication/energy-technology-perspectives-2017---executive-summary.html.

IEA, 2017b. *Renewable Energy for Industry*, Available at: https://www.iea.org/publications/insights/insightpublications/renewable-energy-for-industry.html.

IEA, 2017c. *World Energy Outlook 2017*,

IIASA, 2017. MESSAGE Model Regions. Available at: http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE-model-regions.en.html [Accessed December 21, 2017].

IPCC, 2014. *Climate Change 2014: Mitigation of Climate Change*, Available at: http://www.ipcc.ch/report/ar5/wg3/.

IPPC, 2014. *Climate Change 2014: Mitigation of Climate Change*, Available at: http://www.ipcc.ch/report/ar5/wg3/.

Lafleur, D. et al., 2016. *A Review of current and future methane emissions from Australian unconventional oil and gas production*, Available at: http://www.tai.org.au/content/review-current-and-future-methane-emissions-australian-unconventional-oil-and-gas-production.

Laslett, D. et al., 2017. A large-scale renewable electricity supply system by 2030: Solar, wind, energy efficiency, storage and inertia for the South West Interconnected System (SWIS) in Western Australia. *Renewable Energy*, 113, pp.713–731. Available at: http://www.sciencedirect.com/science/article/pii/S0960148117305244.

Lazard, 2017. *Lazard's Levelized Cost of Energy Analysis - Version 11.0*,

McGlade, C. & Ekins, P., 2015. The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature*, 517(7533), pp.187–190. Available at: http://dx.doi.org/10.1038/nature14016.

Meinshausen, M. et al., 2009. Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature*, 458(7242), pp.1158–1162. Available at: http://dx.doi.org/10.1038/nature08017 [Accessed March 14, 2012].

Meinshausen, M., Raper, S.C.B. & Wigley, T.M.L., 2011. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 1: Model description and calibration. *Atmospheric Chemistry and Physics*, 11(4), pp.1417–1456.

Mella, S., James, G. & Chalmers, K., 2017. *Pre-feasibility study 2017: Evaluating the potential to export Pilbara solar resources to the proposed ASEAN grid via a subsea high voltage direct current interconnector*,

Parkinson, G., 2017. Plunging solar, wind costs means "green" fuel exports could replace coal and gas. *RenewEconomy.com.au*. Available at: http://reneweconomy.com.au/plunging-solar-wind-costs-means-green-fuel-exports-could-replace-coal-and-gas-42114/ [Accessed November 11, 2017].

REneweconomy, 2017a. Elon Musk unveils the long range Tesla Semi electric truck. *RenewEconomy*. Available at: http://reneweconomy.com.au/elon-musk-unveils-the-long-range-tesla-semi-electric-truck-19790/ [Accessed December 21, 2017].

REneweconomy, 2017b. Pilbara Solar eyes NAIF funding for plan to export WA solar to Asia. *RenewEconomy*. Available at: http://reneweconomy.com.au/pilbara-solar-eyes-naif-funding-plan-export-wa-solar-asia-77040/ [Accessed December 15, 2017].

REneweconomy, 2017c. WA mulls three gigawatt-scale PV plants to export solar to Asia. *RenewEconomy*.

Riesz, J. et al., 2016. 100 % Renewables in Australia: A Research Summary. , (March).

Rogelj, J. et al., 2013. 2020 emissions levels required to limit warming to below 2 °C. *Nature Climate Change*.

Rogelj, J. et al., 2015. Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change*, 5(6), pp.519–527. Available at: http://www.nature.com/doifinder/10.1038/nclimate2572.

Rose, B. et al., 2016. Clean Electricity Western Australia 2030 - Modelling Renewable Energy Scenarios for the South West Integrated System. , (April), p.105.

Schleussner, C.-F., Lissner, T.K., et al., 2016. Differential climate impacts for policy relevant limits to global warming: the case of 1.5°C and 2°C. *Earth System Dynamics*, 7(2), pp.327–351. Available at: http://www.earth-syst-dynam.net/7/327/2016/.

Schleussner, C.-F., Rogelj, J., et al., 2016. Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change*. Available at: http://www.nature.com/doifinder/10.1038/nclimate3096.

Scientific Inquiry into Hydraulic Fracturing in the Northern Territory, 2017. *Draft Final Report*, Available at: https://frackinginquiry.nt.gov.au/inquiry-reports/?a=465896.

Shahan, Z., 2017. Renewable Natural Gas from CO2, Water, & Sunlight. *Clean Technica*. Available at: https://cleantechnica.com/2011/11/25/renewable-natural-gas-from-co2-water-sunlight/ [Accessed November 8, 2017].

Teske, S. et al., 2016. 100% Renewable Energy for Australia – Decarbonising Australia's Energy Sector within one Generation. Available at: https://www.uts.edu.au/research-and-teaching/our-research/institute-sustainable-futures/our-research/energy-and-climate-5.

The Western Australian, 2017. Carbon hiccup for Chevron with 5 million-tonne greenhosue gas problem at Gorgon LNG plant. Available at: https://thewest.com.au/business/oil-gas/carbon-hiccup-for-chevron-with-5-million-tonne-greenhouse-gas-problem-at-gorgon-lng-plant-ng-b88694565z.

Turner, R., 2017. Renewable hydrogen could fuel Australia's next export boom after CSIRO breakthrough. *ABC News*, (May). Available at: http://www.abc.net.au/news/2017-05-11/hydrogen-breakthrough-could-fuel-renewable-energy-export-boom/8518916 [Accessed November 8, 2017].

UNEP, 2016. *The Emissions Gap Report 2016*, Available at: http://www.unep.org/pdf/2012gapreport.pdf.

UNEP, 2017. *The Emissions Gap Report 2017*, Available at: www.unenvironment.org/resources/emissions-gap-report.

UNFCCC, 2015. Paris Agreement. *Conference of the Parties on its twenty-first session*, 21932(December), pp.1–16. Available at: http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf.

Veselovskaya, J. V., Parunin, P.D. & Okunev, A.G., 2017. Catalytic process for methane production from atmospheric carbon dioxide utilizing renewable energy. *Catalysis Today*, 298(December 2016), pp.117–123. Available at: http://dx.doi.org/10.1016/j.cattod.2017.05.044.

WAtoday, 2017. "East-to-west" gas pipeline could be on the cards for WA's north. *WAtoday.com.au*. Available at: http://www.watoday.com.au/wa-news/easttowest-gas-pipeline-could-be-on-the-cards-for-was-north-20171201-gzx0pw.html [Accessed December 15, 2017].

World Bank, 2017. *The Growing Role of Minerals and Metals for a Low Carbon Future*, Available at: www.worldbank.org.