CAT Decarbonisation Series - climateactiontracker.org

FOOT OFF THE GAS: INCREASED RELIANCE ON NATURAL GAS IN THE POWER SECTOR RISKS AN EMISSIONS LOCK-IN

June 2017

Climate Action Tracker

Photo: GTS Productions

KEY MESSAGES

- To achieve the Paris Agreement's long-term temperature goal, the power sector needs to rapidly transition to being carbon-free by around 2050.
- This requirement for a complete CO_2 emissions phase-out, combined with increasing competition from renewables, results in a dwindling role for natural gas in the power sector towards the middle of the century despite its ability to balance variable renewables.
- Despite this, many continue to project an increase in gas consumption. Governments and companies are planning significant investments in new natural gas infrastructure, locking in a dependency on fossil fuels, while ignoring the increasing role of low-carbon alternatives.
- This increase in investments, combined with a demand that is likely to decrease, will lead to significant stranded assets in a Paris Agreement-compatible future.
- Natural gas is often perceived as a 'clean' source of energy that complements variable renewable technologies. However, fugitive emissions during gas extraction and transport are an on-going problem. There are numerous options for integrating renewables that reduce and ultimately eliminate the need for natural gas in the power sector.

THE NEED FOR A ZERO CARBON POWER SECTOR

To limit warming to 1.5˚C, as spelt out in the Paris Agreement long term temperature goal, the power sector, which emits over a quarter of global GHG emissions annually (Bruckner et al. 2014), needs to undergo the fastest transition: carbon dioxide emissions from power need to reach zero globally by 2050. "Negative emissions" technologies and approaches for removing CO_2 from the atmosphere will also be needed. This decarbonisation of the power sector needs to happen around ten years earlier than under a 2˚C pathway (Rogelj et al. 2015a).

To achieve this goal, a shift of investments towards zero carbon alternatives needs to be accelerated now from present levels and negative emissions approaches will need to be deployed within a decade or two. Recent model assessments indicate that all coal and oil, and most gas[1] without Carbon Capture and Storage (CSS), will need to be replaced with zero-carbon sources, such as renewables; negative-emission technologies, for example biomass with CCS (BECCS) or alternatives (Rogelj et al. 2015b).

The decarbonisation of the power sector is of great importance, as zero-carbon electricity is the catalyst for achieving emission reductions in other sectors, especially in transport and buildings. A zero-carbon electricity sector will also allow reducing emissions in some of the more challenging sectors, such as the steel sector, where scrap recycling—relying on renewable electricity—could significantly reduce emissions coming from primary steel production.

On the future of gas in the power sector, we find that many projections, including from the IEA, and expectations of some investors—including many governments—not only fail to consider the need for complete decarbonisation within three decades, but also ignore the increasing role and potential of low and zero carbon alternatives. Current investment in new gas infrastructure increases the risk of stranded assets, paving the way to a fossil fuel dependency that runs contrary to the Paris Agreement.

THE INCREASING ROLE OF GAS IN THE POWER SECTOR

The power sector needs to undertake the fastest transition to decarbonise—and there has already been some success. The global CO_2 intensity of electricity has decreased slightly: from 533 g/kWh in 1990 to 519 g/kWh in 2014 (CAT 2017). However, the trend has not been the same for the biggest emitters. While the emissions intensity of power in this period dropped by 26% in China, 18% in the USA and 36% in the EU, it has increased by 10% in India. These reductions are not fast enough for decarbonisation by mid-century (Figure 1).

[1] When not specified otherwise, we use the term 'gas' to mean natural gas. We explicitly mention the role of biogas below.

NEW CLIMATE INSTITUTE · ECOFYS A Navigant Company · CLIMATE ANALYTICS

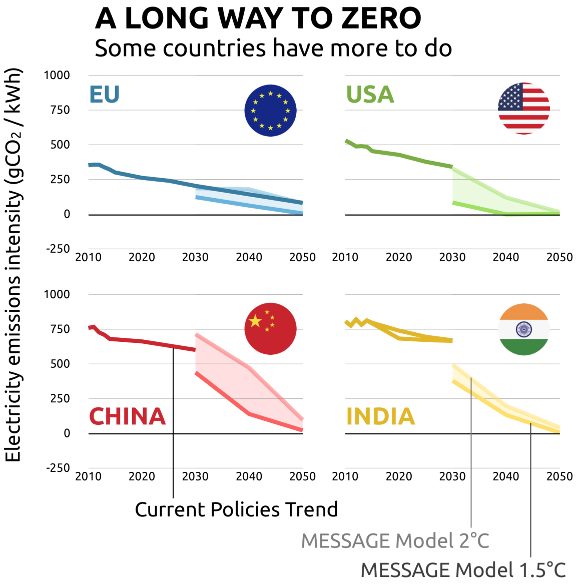

Figure 1: Projections of emissions intensity trends of electricity based on current policies compared to 1.5°C and 2°C scenarios (based on MESSAGE Model (IIASA 2016)*)*

Globally, the share of electricity generated from gas increased from 15% in 1990 to 22% in 2014, with significant differences across countries (IEA 2016b). The most important change for global gas consumption occurred in the United States, where, in 2016, after an increase of 54% over ten years, natural gas surpassed coal as the main source of power for the first time (EIA 2017).

In gas-importing countries such as India, South Africa, or China, the role of gas is mostly limited to meeting peak demand, and providing balancing power (IEA 2016c).

In Japan, the largest liquefied natural gas (LNG) importer in the world, gas-fired power plants replaced a large share of nuclear energy after the catastrophe in Fukushima (Stiles 2016). This increase in gas consumption may only be temporary as investment in energy efficiency leads to a continuous decrease in power consumption (Enerdata 2016), and renewables development is gaining momentum. Brazil is targeting an increasing role of natural gas to limit its dependency on hydro-energy (70% of total electricity (IEA 2016a)), which has led to power shortages. For this reason, Brazil's government has recently opened its capacity auctions to thermal power plants (Bloomberg 2015). In 2015, almost 13% of power in Brazil was produced from natural gas, although its share strongly fluctuates from year to year, depending on the power generation from hydro (Ministry of Mines and Energy 2016). Australia, the second largest liquefied natural gas exporter, generated 21% of its power at home by natural gas in 2015; a share projected to slightly decrease to 15% in 2021 before increasing back to 19% by 2030 (Australian Government 2016a; Australian Government 2016b).

GAS IS NOT A LONG-TERM SOLUTION TOWARDS DEEP DECARBONISATION

Even though gas has played an important role in modestly improving the carbon intensity of the power sector over the last decade, it is not a viable long-term solution to mitigating climate change. A deep decarbonisation of the power sector requires a radical shift away from fossil fuels. This includes ultimately phasing out natural gas: Given the increased energy needs for CCS, a power plant with CCS could reduce CO_2 emissions by approximately 80–90% compared to a plant without CCS (IPCC 2007; Rubin et al. 2015). Although CCS can reduce emissions from gas significantly, capture rates above 90% have not been fully explored and it is uncertain whether this could be achieved at acceptable cost. CCS can also require significant additional water for cooling or processing, risking an increased water stress in already water scarce regions (Fricko et al. 2016).

The popularity of gas is partly due to its perception as a so-called "bridge technology" that provides operational flexibility to support the integration of renewables such as wind and solar. Some use this argument to advocate for a switch from coal to gas as a lower-carbon alternative. While gas can certainly play a role as a bridging fuel, it too, like coal, faces a rapidly diminishing role in both a well below 2°C, and a 1.5°C-consistent transformation—for the following reasons:

Emissions for power from unabated natural gas are incompatible with power sector decarbonisation: life-cycle emissions, i.e. taking into account the emissions in the fuel chain and the manufacturing of the energy conversion technology, are estimated at 410–650 gCO_2eq/kWh for natural gas combined-cycle plants. This is lower than power from hard coal (710–950 gCO_2eq/kWh), but much higher than for most renewable technologies (2–180 gCO_2eq/kWh) (IPCC 2014).

It is therefore not surprising that Integrated Assessment Models (IAMs), in strategies that lead to lowest overall cost, phase out gas without CCS entirely by 2050. Initial model results for 1.5°C compatible emissions pathways suggests a share of around 15% or less for gas with CCS in 2050 in the power mix, phased out again by 2070 (Rogelj et al. 2013; personal communication).

There are still emissions associated with this: Life-cycle emissions for gas power plants with CCS are strongly influenced by the amount of methane lost during production and transport. Assuming a leakage between 0.8%–5.5% they can range between 90 and 370 gCO_2eq/kWh (IPCC 2014).

Significant advances would have to be made both in methane leakage reduction and in CCS capture rates to decrease these emission values. This is challenging, especially given the difficulty in monitoring and verification of methane leakage (IEA 2016c). Thus, to reach zero (or negative) emissions, the residual emissions from CCS-enabled gas would have to be balanced out by negative emissions technologies.

Although it is conceivable to decarbonise power from gas based on the technical approaches above, **it is unlikely that there would be a role for gas with CCS in the evolving power system**: the increasing market share of renewables due to their rapid cost decline will leave only a small part of the electricity supply for non-renewables in most regions. This will add further **cost-pressures as the gas plant will not run at all times, called low capacity factors** (the capacity factor of a power plant is the fraction of time in which the plant actually produces power). The competitiveness of renewables versus gas with CCS is often underestimated in IAMs. One reason resides in the slower reduction of renewables' costs in such models, for instance compared to the recent rapid decline. At least as important is the fact that, due to implicit or explicit structural assumptions, IAMs are inclined to propagate energy systems with a historical, or present-day, analogue. For example, systems with a constant base load provided by natural gas with CCS are easier to model by the IAMs than novel system configurations in which gas, or indeed any alternative, is used as a modulating/balancing energy source complementing a large share of variable renewables.

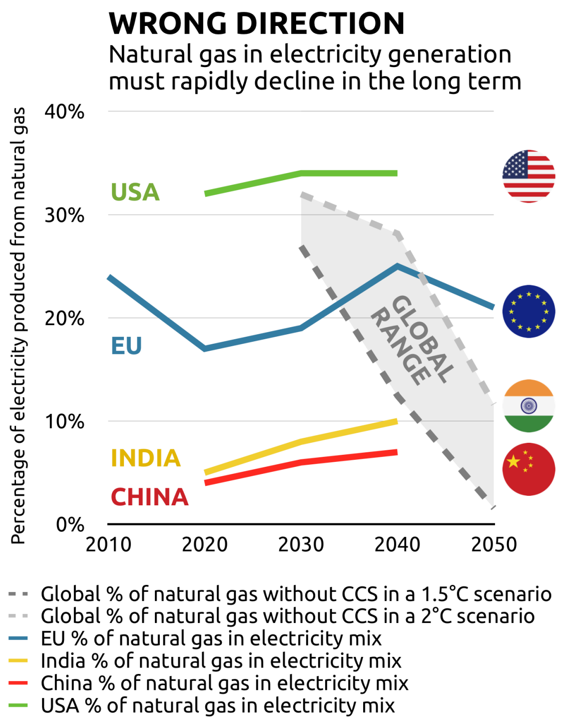

Figure 2: Projected share of electricity from natural gas compared with the range of global scenarios consistent with 1.5°C/2°C concerning the share of electricity from gas without CCS. Calculations based on MESSAGE (IIASA 2016), *IEA WEO Current Policy Scenario* (IEA 2016b) *and Climate Action Tracker analysis.*

The CAT warned in 2014 that "replacing coal with gas, as proposed by some, is clearly not an option, as it would only reduce warming by about 0.1°C" (Climate Action Tracker 2014). Given that remaining emissions from gas would still be substantially higher than emissions related to renewables, we concluded the "reduction in warming projected by 2100 achieved with a switch from coal to gas is only 25–45% of what is obtained with a switch to renewables."

Natural gas can, however, be replaced by biogas, which can be fed into the existing natural gas grid. Some initial investments are still needed for the planning and construction of feed-in facilities, depending on the connection parameters. Like natural gas, biogas can be used to generate electricity and heat as a fuel, or as chemical feedstock. The life-cycle emissions of biogas would depend critically on the sourcing and production methods used.

EXPECTED GROWTH IN GAS DEMAND FAILS TO MATERIALISE

According to the 2011 IEA Special Report on gas, demand for natural gas was set to increase due to lower growth in nuclear energy, increasing utilisation of gas in the transport sector, and replacing coal by "cleaner" sources of energy. The IEA predicted low prices resulting from the exploration of shale gas would drive this increasing gas consumption. As a result, their optimistic "Gas Scenario" projected a global increase in gas demand by 54% between 2010 and 2035 (IEA 2011).

While the IEA, in its latest edition of the World Energy Outlook, was less optimistic about the increase of gas in comparison to its earlier estimates, in its New Policies Scenario it still predicts an annual average increase in gas demand of 1.5% by 2040 (IEA 2016c); see also Table 1.

The projected increase in demand would not be distributed equally. In a number of regions, gas demand is expected to increase significantly between 2014 and 2025: in China by 105%, India by 90%, Middle East by 29% and Africa by 31%, while in the others it is projected to decrease (Japan -27%) or remain relatively stable (Latin America +7%) (IEA 2016c).

The projected increased gas demand is also mirrored in the share of gas in the electricity mix which, according to the IEA, would rise in the major economies of the US, the EU, China and India (Figure 2). These projections run counter to the global 1.5°C pathway, which requires a steep reduction of gas in the electricity mix, risking the accumulation of stranded assets.

	Demand in 2014 (in bcm)	Demand in 2025 (in bcm)	Increase in demand
World	3 502	4 106	17%
United States	756	807	7%
European Union	462	515	11%
China	188	386	105%
India	50	95	90%
Middle East	441	570	29%
Africa	131	171	31%
Latin America	165	177	7%
Japan	129	94	-27%

Table 1: Projected increase in natural gas demand between 2014 and 2025 according to IEA's New Policies Scenario. Calculations based on (IEA 2016c)

Recent developments in the countries and regions where the IEA projected gas would grow the fastest indicate the increase may be much slower—due to the rise of renewables.

Even though China's gas consumption rose by 8.5% in 2016, the share of energy from nuclear increased by almost 26%, and from wind by 19%. Both wind and solar covered almost 8% of power supply (National Bureau of Statistics of China 2016) in contrast to the IEA's projection of 7.2% for 2020 in its Current Policy Scenario. The role of PV has also increased, with installed capacity reaching 77 GW in 2016: almost twice as much as in the previous year (Reuters 2017). The role of solar energy is especially important due to its ability to provide electricity during the midday peak hours usually covered by natural gas power plants.

Several other countries where the role of gas was projected to increase are instead speeding up the development of renewables. India has doubled its PV target to 40 GW for 2020 (Enerdata 2017). In Middle Eastern countries the popularity of alternatives to fossil fuels is facilitated by climate and geographic location with high solar resource availability, allowing it to reach record low prices of 2.42 cents per kilowatt hour in 2016 (Fortune 2016). High solar resource availability combined with favourable policy settings have triggered a rapid uptake of solar PV in Australia (REN21 2017). Current high domestic gas prices are contributing to high electricity prices in this country, further increasing the competitiveness of renewables.

This shows that planned gas projects will have to adapt to a new market situation where renewables will be the major source of energy.

Even if natural gas will be used for some time to balance the grid, its role is set to decrease.

ENERGY TRANSFORMATION WITHOUT NATURAL GAS IS POSSIBLE

The argument that gas contributes to the flexibility of the power grid has been weakened by an increasing number of alternative solutions that could achieve the same effect (Papaefthymiou et al. 2014).

Expansion of electricity grids could balance the differences between power generation from weather-dependent renewables in different regions and countries (IRENA 2013). Increasing interconnectivity would also allow different countries to benefit from different energy mixes, e.g. balancing hydro-energy from Norway with wind energy in Denmark.

Demand management, which takes advantage of the flexibility offered by (big) energy consumers, could offer new business opportunities for companies able to increase or decrease their power consumption demand (Eurelectric 2015). Renewables also include some dispatchable sources of energy such as hydro-energy or biogas, which can be used to balance the differences in weather-dependent renewables.

Additional flexibility could also be added by sectoral integration. Increasing utilisation of electricity in the transport sector can flatten demand and supply peaks by intelligently managing battery charging. Electricity could also be flexibly used for the generation of hydrogen. A significant potential for relatively cheap, storage opportunities is offered by the heating sector (IEA 2014). In both cases, electricity from renewables could effectively decrease the need for gas consumption.

Storage—both small and large-scale—would mitigate the seasonal and diurnal variations in power generation (IEC 2012). Large scale storage is increasingly used by individual power producers to allow them to consume their own power during the night. Seasonal storage, addressing the so-called 'windless winter week', is especially in need of additional solutions (Ecofys 2016). These could involve battery, compressed air or hydrogen storage, but also production and storage of biomethane using some parts of the existing methane transport and storage infrastructure.

THE CO-BENEFITS OF AN ENERGY TRANSFORMATION AWAY FROM GAS

The transition towards a decarbonised world is not only necessary to honour the commitments made under the Paris Agreement's "to pursue efforts to limit the temperature increase to 1.5°C", but brings a whole array of opportunities that clearly demonstrate that tackling climate change makes economic sense.

Accelerated decarbonisation efforts can improve energy independence, especially for those countries reliant on fuel imports (UNDP 2016). IRENA (2016a) estimated that in 2015 renewable energy employed 8.1 million people around the world (excluding large hydropower). In the US, the solar energy sector employed almost twice as many people as coal-, gas- and oil-fired power generation combined (U.S. Department of Energy 2017). Doubling the share of renewables in the energy mix by 2030 would support over 24 million jobs in the sector (IRENA 2016b).

THE RISK OF STRANDED ASSETS – DON'T MAKE THE SAME MISTAKE TWICE

In the IEA's New Policies Scenario, an increasing global gas demand would mostly be covered by LNG, which would increase its share from 42% in 2014 to 53% in 2040, and lead to projected investments of close to $2.2 trillion in gas transmission and distribution in the period 2016–2040 (IEA 2016c).

The main challenge with these investments is the capital-intensity of the necessary infrastructure, especially LNG ports and pipelines. An example is the Nord Stream pipeline under the Baltic Sea, which cost $7.4 billion (Nord Stream 2013). An LNG terminal may cost between $1.1 and $8.8 billion (Quirijns 2015). The payback period of such significant investment strongly depends on the utilisation rate of this infrastructure, which depends on the gas demand and the existence of alternative routes of gas transportation.

Due to the decreasing costs and increasing role of alternatives, demand for natural gas is unlikely to increase as rapidly as projected. Despite this, significant numbers of new LNG ports and pipelines are now under construction. According to the IEA (2016c), markets will struggle to absorb the additional 130 bcm of liquefaction capacity scheduled to come online in the next few years around the world.

The United States is investing in a number of new gas pipelines, some of which would bring fuel to export terminals (EIA 2016). Some predictions state a further $30–55 billion will have to be invested in LNG infrastructure in the USA and Canada by 2035 to satisfy the projected increase in gas consumption (PGJ 2016). This is despite the fact that the average utilisation of the existing gas capacity in the USA is only around 54% (US Department of Energy 2015).

In Europe, the conflict in Ukraine accelerated the numerous attempts to provide alternatives to Russian sources of gas. As a result, massive investments in new gas pipelines and LNG ports have been initiated or planned. But with an overall utilisation rate close to 25%, many ports remain unused (European Parliamentary Research Service 2015).

In Europe, massive investments in new gas pipelines and LNG ports have been initiated, planned and proposed as part of a strategy to increase security of supply, including through accessing alternatives to Russian sources of gas. The overall utilisation rate of existing LNG ports is close to 25%, with many ports remaining unused (European Parliamentary Research Service, 2015). If the proposed four gas pipelines (including Nord Stream II) and total of 39 LNG ports materialised, this would increase the EU gas import capacity by 58% (Gaventa et al. 2016).

In Australia, contrary to the government's consideration of subsidising gas pipelines in the north of the country (The Guardian 2017), the largest energy company, AGL Energy argues that the role of natural gas will decrease. Large scale renewables with storage are becoming cheaper than power from gas (REnewEconomy 2017).

In addition to a significant increase in the transport infrastructure, countries are investing in new gas exploration, mainly from non-conventional resources. Brazil is investing in oil and natural gas production from offshore fields. The challenging geological environment makes extraction difficult and very costly (IEA 2013).

Investments in gas infrastructure, especially in the exploration of non-conventional and thus more expensive resources, may lead to significant stranded assets in the future, if projected demand increases do not materialise. In addition, unless plans are in place for replacing natural gas with alternatives, such as biomethane, in the medium term, these investments could lock countries into an emissions pathway that is inconsistent with the goal of the Paris Agreement. To achieve decarbonisation in a cost effective and timely manner, national and subnational governments need to accurately plan for resources, and keep in mind their utilisation rates.

CONCLUSION

The Paris Agreement long-term temperature goal requires a complete decarbonisation of the power sector by 2050. This leaves little space for any kind of fossil fuel, including natural gas.

Natural gas only has a very short "bridge" to renewables. Even if coupled with CCS, current evidence suggests significant emissions would still occur which would require additional abatement strategies or balancing with negative emissions technologies. Additional cost pressures arise from the increasing market share of cheap renewables.

Even if gas may play a role in balancing weather-dependent renewables in the short-term, there are numerous alternatives to the role of natural gas in increasing the flexibility of the power grid, such as storage, grid development, demand management or flexible renewables.

A mix of these solutions will make it possible to deal with a fully renewable power grid without relying on natural gas. To achieve this purpose, a significant shift in investment away from new natural gas infrastructure and towards renewable source of energy is necessary.

Massive investments in gas extraction, new pipelines and LNG ports—in addition to what is already existing and often underutilised—will divert financial resources from investments into a decarbonised power sector, and lead to the creation of stranded assets in the coming decades, constituting a major obstacle for the full decarbonisation of the electricity sector.

AUTHORS

Climate Analytics
Jasmin Cantzler
Andrzej Ancygier
Fabio Sferra
Michiel Schaeffer
Bill Hare
Matt Beer

NewClimate Institute
Sebastian Sterl
Markus Hagemann

Ecofys
Lindee Wong
Yvonne Deng
Karlien Wouters
Timme van Melle
Kornelis Blok

This work was funded by the ClimateWorks Foundation

BIBLIOGRAPHY

Australian Government, 2016. Australian Energy Update 2016. https://industry.gov.au/Office-of-the-Chief-Economist/Publications/Documents/aes/2016-australian-energy-statistics.pdf

Australian Government, 2016. Australia's emissions projections 2016. http://www.environment.gov.au/climate-change/publications/emissions-projections-2016

Bloomberg, 2016. Clean-Energy Jobs Surpass Oil Drilling for First Time in U.S. - Bloomberg. Available at: https://www.bloomberg.com/news/articles/2016-05-25/clean-energy-jobs-surpass-oil-drilling-for-first-time-in-u-s.

Bloomberg, 2015. Thermal Developers Win 82% of Contracts in Brazil Energy Auction. Available at: https://about.bnef.com/blog/thermal-developers-win-82-of-contracts-in-brazil-energy-auction/.

Bruckner, T. et al., 2014. Energy Systems. In O. Edenhofer et al., eds. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. Available at: http://report.mitigation2014.org/report/ipcc_wg3_ar5_chapter7.pdf.

CAT, 2017. Data & Trends. http://climateactiontracker.org/decarbonisation/intro

Climate Action Tracker, 2014. *Rapid phase out of coal essential, but not enough to hold warming below 2°C*, Available at: http://climateactiontracker.org/assets/publications/briefing_papers/CAT_BKM_2014.09.22_PRESS_DISTRIBUTION_final.pdf.

Ecofys, 2016. Windless winter weeks: The impact of future heating supply on the energy infrastructure. Available at: http://www.ecofys.com/en/news/windless-winter-weeks-the-impact-of-future-heating-supply-on-the-energy-inf/.

EIA, 2017. Net Generation by Energy Source. Available at: https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_1.

EIA, 2016. New pipeline projects increase Northeast natural gas takeaway capacity - Today in Energy - U.S. Energy Information Administration (EIA). Available at: http://www.eia.gov/todayinenergy/detail.php?id=24732.

Enerdata, 2016. Electricity domestic consumption. https://yearbook.enerdata.net/electricity-domestic-consumption-data-by-region.html

Enerdata, 2017. India doubles its solar power capacity target to 40 GW by 2020. Available at: https://www.enerdata.net/publications/daily-energy-news/india-doubles-its-solar-power-capacity-target-40-gw-2020.html.

Eurelectric, 2015. *Designing fair and equitable market rules for demand response aggregation*, Available at: http://www.eurelectric.org/media/169872/0310_missing_links_paper_final_ml-2015-030-0155-01-e.pdf.

European Parliamentary Research Service, 2015. Liquefied Natural Gas in Europe. Available at: http://www.europarl.europa.eu/RegData/etudes/BRIE/2015/571314/EPRS_BRI(2015)571314_EN.pdf.

Fortune, 2016. A Jaw-Dropping World Record Solar Price Was Just Bid in Abu Dhabi. Available at: http://fortune.com/2016/09/19/world-record-solar-price-abu-dhabi/.

Fricko, O. et al., 2016. Energy sector water use implications of a 2 °C climate policy. *Environmental Research Letters*, 11(3), p.034011. Available at: http://stacks.iop.org/1748-9326/11/i=3/a=034011?key=crossref.51c76d74f6452def9976da455cdaae28.

IEA, 2011. *Are we entering a golden age of gas? Special Report*, Available at: http://www.worldenergyoutlook.org/media/weowebsite/2011/WEO2011_GoldenAgeofGasReport.pdf.

IEA, 2016a. *Energy Statistics and Balances*, Paris, France.

IEA, 2014. *Linking Heat and Electricity Systems*, Available at: https://www.iea.org/publications/freepublications/publication/LinkingHeatandElectricitySystems.pdf.

IEA, 2013. *World Energy Outlook 2013*, Available at: https://www.iea.org/publications/freepublications/publication/WEO2013.pdf.

IEA, 2016b. *World Energy Outlook 2016*,

IEA, 2016c. *World Energy Outlook 2016*, Paris, France: International Energy Agency. Available at: http://www.oecd-ilibrary.org/energy/world-energy-outlook-2016_weo-2016-en.

IEC, 2012. *Grid integration of large-capacity Renewable Energy sources and use of large-capacity Electrical Energy Storage*, Available at: http://www.iec.ch/whitepaper/pdf/iecWP-gridintegrationlargecapacity-LR-en.pdf.

IIASA, 2016. MESSAGE. Available at: http://www.iiasa.ac.at/web/home/research/modelsData/MESSAGE/MESSAGE.en.html.

IPCC, 2014. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler]*, Cambridge, UK; New York, NY, USA.

IPCC, 2007. IPCC Special Report Carbon Dioxide Capture and Storage: Summary for Policymakers. , 3(2300), pp.151–200. Available at: http://www.gispri.or.jp/kankyo/ipcc/ipccreport.html.

IRENA, 2016a. *Renewable Energy and Jobs*, Available at: http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Jobs_Annual_Review_2016.pdf.

IRENA, 2016b. *Renewable Energy Benefits: Measuring the Economics*, Available at: http://www.irena.org/DocumentDownloads/Publications/IRENA_Measuring-the-Economics_2016.pdf [Accessed January 9, 2017].

IRENA, 2013. *Smart Grids and Renewables. A Guide for Effective Deployment*, Available at: https://www.irena.org/DocumentDownloads/Publications/smart_grids.pdf.

Ministry of Mines and Energy, 2016. Monthly Energy Bulletin- Brazil. Available at: http://www.mme.gov.br/documents/10584/3580500/01+-+Monthly+Energy+Bulletin+(May+2016+-+Brazil)+(PDF)/04c29782-75db-4097-b96c-88a71a4be23e;jsessionid=400CECF835A6C708518EDD6744CF5CF3.srv154?version=1.4.

National Bureau of Statistics of China, 2016. 能源产品产量. Available at: http://data.stats.gov.cn/tablequery.htm?code=AA0701.

Nord Stream, 2013. *Nord Stream by Numbers*, Available at: https://www.nord-stream.com/download/file/documents/pdf/en/2013/11/nord-stream-by-the-numbers_177_20131128.pdf.

Papaefthymiou, G., Grave, K. & Dragoon, K., 2014. *Flexibility options in electricity systems*, Ecofys Germany. Available at: http://www.ecofys.com/en/projects/flexibility-options-in-electricity-systems.

PGJ, 2016. US, Canada to Require $546 Billion in Gas, Oil and NGL Infrastructure Investment. Available at: https://pgjonline.com/2016/04/12/us-canada-to-require-546-billion-in-gas-oil-and-ngl-infrastructure-investment/.

Quirijns, S., 2015. *LNG Regasification Terminals. A literature study into the world of LNG*, Available at: https://repository.tudelft.nl/islandora/object/uuid:3cf91cf8-2288-48fb-a445-cd0860196a17/datastream/OBJ1/download.

REN21, 2017. Renewables 2017. Global Status Report. http://www.ren21.net/gsr-2017/

REnewEconomy, 2017. AGL kills idea of gas as transition fuel: wind, solar + storage cheaper.

Reuters, 2017. China's solar power capacity more than doubles in 2016. Available at: http://www.reuters.com/article/us-china-solar-idUSKBN15J0G7.

Rogelj, J. et al., 2013. 2020 emissions levels required to limit warming to below 2°C. *Nature Clim. Change*, 3(4), pp.405–412. Available at: http://dx.doi.org/10.1038/nclimate1758.

Rogelj, J. et al., 2015a. 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.

Rogelj, J. et al., 2015b. 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 [Accessed October 19, 2016].

Rubin, E.S., Davison, J.E. & Herzog, H.J., 2015. The cost of CO2 capture and storage. *International Journal of Greenhouse Gas Control*, 40, pp.378–400. Available at: http://www.sciencedirect.com/science/article/pii/S1750583615001814.

Stiles, T., 2016. Demand for liquefied natural gas in Japan after Fukushima. Available at: https://lercpa.org/lng-japan/.

The Guardian, 2017. Turnbull says government could subsidise gas pipelines and Adani rail.

UNDP, 2016. *Low Carbon Monitor 2016: Pursuing the 1.5°C limit - Benefits and Opportunities*, Available at: http://www.thecvf.org/wp-content/uploads/low-carbon-monitor.pdf.

U.S. Department of Energy, 2015. Natural Gas Infrastructure Implications of Increased Demand from the Electric Power Sector. Available at: http://energy.gov/sites/prod/files/2015/02/f19/DOE Report Natural Gas Infrastructure V_02-02.pdf.

U.S. Department of Energy, 2017. U.S. Energy and Employment Report. https://www.energy.gov/sites/prod/files/2017/01/f34/2017%20US%20Energy%20and%20Jobs%20Report_0.pdf

Westbrook, T., 2017. Australia provincial government approves start of $600 million gas pipeline | Reuters. Available at: https://www.reuters.com/article/us-australia-gas-pipeline-idUSKBN18Z0F3.