

From climate pariah to climate saviour?

What the petroleum industry can do about climate change

This paper outlines four key areas in which the oil and gas industry can contribute to climate action while acting in its own interest – carbon pricing, supply chain leakage, addressing permafrost methane emissions and biofuels/biochar production

Discussion paper

Andrew Hopkins, Australian National University
July 2016

ABOUT THE AUSTRALIA INSTITUTE

The Australia Institute is an independent public policy think tank based in Canberra. It is funded by donations from philanthropic trusts and individuals and commissioned research. Since its launch in 1994, the Institute has carried out highly influential research on a broad range of economic, social and environmental issues.

OUR PHILOSOPHY

As we begin the 21st century, new dilemmas confront our society and our planet. Unprecedented levels of consumption co-exist with extreme poverty. Through new technology we are more connected than we have ever been, yet civic engagement is declining. Environmental neglect continues despite heightened ecological awareness. A better balance is urgently needed.

The Australia Institute's directors, staff and supporters represent a broad range of views and priorities. What unites us is a belief that through a combination of research and creativity we can promote new solutions and ways of thinking.

OUR PURPOSE - 'RESEARCH THAT MATTERS'

The Institute aims to foster informed debate about our culture, our economy and our environment and bring greater accountability to the democratic process. Our goal is to gather, interpret and communicate evidence in order to both diagnose the problems we face and propose new solutions to tackle them.

The Institute is wholly independent and not affiliated with any other organisation. As an Approved Research Institute, donations to its Research Fund are tax deductible for the donor. Anyone wishing to donate can do so via the website at <https://www.tai.org.au> or by calling the Institute on 02 6130 0530. Our secure and user-friendly website allows donors to make either one-off or regular monthly donations and we encourage everyone who can to donate in this way as it assists our research in the most significant manner.

Level 5, 131 City Walk

Canberra, ACT 2601

Tel: (02) 61300530

Email: mail@tai.org.au

Website: www.tai.org.au

Summary

This paper addresses the question: what things can the petroleum industry do *in pursuit of its economic interests* that will also help to reduce greenhouse gas levels in the atmosphere?

The industry has accepted that climate change is real and human-induced, and has even accepted in principle that a price on carbon is desirable. However, as a whole the industry is not lobbying for such a price. The first thing it should do is lobby for a significant price on carbon. This will obviously be beneficial in combatting climate change. It will also be advantageous to the petroleum industry, because it will impact more heavily on coal and assist in bringing coal fired power to an end, leaving the way open for gas, at least in the short term.

Gas is only preferable to coal, from an emissions point of view, if methane emissions from all the links in the gas supply chain are curbed. Controlling these emissions will not only benefit the environment; it will also be cost effective for the industry.

Even if we get to zero human emissions, climate change has already triggered an increase in the rate of methane release from the Arctic permafrost. The petroleum industry is well placed to capture this methane and either burn it, thereby reducing its greenhouse potential, or better still transport it to market. Appropriate financial incentives could make this worthwhile for the industry.

Finally, even if emissions can be stopped, we need to draw down carbon from the atmosphere and store it long term. One of the processes by which biofuels are made can be modified to maximise the production of biochar which can then be stored for a thousand years. The industry is well placed to do this, provided there are appropriate financial incentives.

These last two processes - capturing Arctic methane emissions and drawing down carbon from the atmosphere - if they can be done on a large scale, have the potential to transform the industry into a climate saviour.

Table of Contents

Summary.....	1
1. Introduction.....	4
“Getting into renewables”: a history lesson	4
Four areas of common ground	6
2. The current petroleum industry position on climate change	9
The coal industry position on pricing carbon	13
Portfolio companies	16
Summing up.....	17
3. Why the petroleum industry should advocate a price on carbon	18
Replacing coal with gas.....	18
Environmentalist concerns about replacing coal with gas.....	19
Parting company with coal	20
Energy companies.....	21
Solar thermal	22
4. Reducing methane emissions	24
Supply chain leakage	24
Urban gas pipeline leakage.....	27
Catastrophic storage failures.....	28
5. Capturing Permafrost Releases	32
Cryosphere amplifiers.....	32
Permafrost.....	33
Exploiting methane clathrates.....	34
A role for the gas industry	35
6. Removing carbon from the atmosphere	37
Pyrolysing algae	37
The petroleum industry	39
7. Carbon capture and storage	41
Storage.....	41
Capture	42

The ultimate issue	43
8. Conclusion	44
Recommendations.....	45
To the petroleum industry	45
To governments.....	45
About the Author.....	46
Endnotes.....	47

1. Introduction

This paper is about the contribution that the oil and gas industry can make to combatting climate changeⁱ. The petroleum industry is often viewed as part of the problem, so it may seem as first sight paradoxical, even heretical to some, to suggest the industry has a role to play in solving the problem. The fact is however that there is common ground between the petroleum industry and those worried about climate change. The purpose of this paper is to explore that common ground. The question I shall address is this: what things can the petroleum industry do *in pursuit of its economic interests* that will also help to reduce greenhouse gas levels in the atmosphere? In other words, what are the win/win options? I don't imagine there is a long term future for the industry in its present form, unless there are extraordinary developments in the technology of carbon capture and storage. But in the short to medium term it will turn out that there is much that the industry can do to combat greenhouse gases, without jeopardising its own economic viability. Petroleum companies need to identify and pursue these win/win options vigorously, because if they don't, "what remains of their existence will be nasty, brutish and short"ⁱⁱ.

“GETTING INTO RENEWABLES”: A HISTORY LESSON

The first petroleum company to embrace the idea that combatting climate change might be good business was BP (British Petroleum). It is a story worth recounting, if only to identify some of the issues and pitfalls. BP's commitment to this idea was announced with a fanfare by its CEO, John Browne, in a major speech in 1997. It culminated in the year 2000 with the rebranding of BP as "beyond petroleum". The accompanying logo, a green and yellow sun that looked much like a flower, was meant to symbolise this transformation. As it transpired, there were two important prongs to Browne's strategy - a green energy initiative and advocacy of a price on carbon.

BP's green energy initiative involved the creation of a new division of BP - a solar panel business - BP solar. According to the president of BP Solar America, "solar [will be] brought to the main table ... Previously there were just three businesses: oil, exploration, and chemicals. Now there are four. Solar will be developed to become one of the main products of our company."ⁱⁱⁱ Unfortunately this lofty ambition was never realised. The company did spend a few hundred million dollars acquiring various solar panel manufacturing plants and became for a short while the world's largest

manufacturer of solar panels^{iv} (bearing in mind of course that the industry was then in its infancy). But Browne refused to make a big investment in BP's solar business, leading environmentalists, to claim that the new direction was no more than "greenwash". The fact is that BP's solar business always struggled and finally shut down in 2011.^v Here is how one observer explained this outcome.

The solar panel business had absolutely no overlap with BP's competencies. First, solar was not an energy business but a manufacturing business. It was firmly in the electrical goods camp ... that oil companies knew nothing about. Secondly, oil companies weren't really customer-facing. They had fuel retail operations but these made little money and were gradually abandoned from the late 1990s onwards (although the companies who bought their stations often retained the oil majors' branding). Thirdly, solar deviated from BP's core skills because it was small. BP marketed itself to resource holders [investors] as a company with a special expertise in big things.^{vi}

In short, BP tried and failed to enter the green energy market. This was a highly visible failure. Having adopted and publicised the name, "beyond petroleum", BP now had to abandon it, just as it had abandoned its original name, "British Petroleum".

The other main prong of BP's strategy was to accept and indeed advocate a price on carbon. As Browne saw it, this would be beneficial for the oil and gas industry. Coal produced considerably more carbon dioxide per unit of energy than did gas - approximately twice as much - and so a price on carbon would encourage electricity generators to switch from coal to gas. Since most of the major oil and gas companies had shed their coal interests in the 1990s^{vii}, this strategy would benefit the oil and gas majors, at the expense of coal mining companies. BP was among a number of oil and gas companies that began advocating a price on carbon for this reason. This is one of the areas where the petroleum industry has common ground with the climate movement, as I shall discuss in more detail shortly. Indeed, a price on carbon continues to be the policy of many of the oil and gas majors.

BP was not the only petroleum company to test the waters with renewables. At the beginning of this century Shell was developing its own solar business, but sold much of it in 2006 and suspended all investment in renewables in 2009^{viii}. At the present time its investment in wind appears to be increasing, but just as with BP, Shell has no intention of directing a significant part of its investment to renewables. Its CEO is reported to have said recently that he does not want to get so far out in front that he dilutes investor returns, but he does want to make sure Shell is at the leading edge of the transition to lower-carbon economies^{ix}.

Petroleum companies clearly don't want to be left behind in the transition to renewables, but equally, they don't intend to show the way. This paper will therefore say no more about renewables and concentrates instead on areas in which the petroleum industry can make a distinctive contribution.

FOUR AREAS OF COMMON GROUND

There are at least four areas of common ground, four win/win options.

First, as already flagged, a price on carbon will benefit both the oil and gas industry and the environment, by encouraging a transition from coal to gas. A price on carbon will also encourage the renewable energy industry, which must become the main source of energy in the not too distant future if we are to avoid catastrophic climate change. That means of course that in supporting a price on carbon, the petroleum industry will be helping to dig its own grave in the longer term, but in the shorter term it is a happy coincidence for the industry that a price on carbon will benefit it, as well as the renewable energy industry.

The second area of common ground concerns the need to minimize methane (natural gas) emissions. Methane is a far more environmentally damaging gas than carbon dioxide - 80 to 100 times more damaging. Obviously reducing methane emissions will be enormously advantageous in the fight against climate change. There are several ways in which the petroleum industry is currently emitting methane. For a start, the gas distribution pipelines that service our cities in some parts of the world leak like sieves. Moreover, gas from coal seams and shale beds is harvested using a bewildering network of wells and pipes. A significant amount of this gas is lost in the process. If all these losses can be curtailed, there will be more gas for sale and less impact on the environment. Finally, a great deal of gas is stored in large natural underground reservoirs, to be drawn on in the peak demand period of winter. A recent failure of one of these reservoirs in southern California released massive amounts of methane into the atmosphere, making it impossible for California to meet its emission targets. Underground reservoirs are out of site and out of mind until something like this happens, but more effective management of the risk of such releases is in the economic interest of the companies concerned, as well being environmentally beneficial.

A third area of common ground concerns Arctic methane emissions. Even if we get to zero human emissions in the not too distant future, we have already triggered various accelerators that are likely to lead to runaway climate change unless we can do something about them. One of these accelerators is the melting of the permafrost

areas of the Arctic. There is a massive amount of methane trapped in the permafrost which is now starting to be released as a result of global warming that has already occurred. The more of this methane that is released into the atmosphere, the greater the global warming effect and the more rapidly the permafrost will melt. Not surprisingly, this is described as a climate change accelerator or amplifier. Unfortunately we cannot solve this problem simply by taking our collective foot off the accelerator. It is too late for that. We need to find a way to put a brake on the process. Here is where the petroleum industry comes in. It should not be beyond the imagination of the industry's clever engineers to develop a technology to harvest this gas, as it is released or just prior to its release from the permafrost. Coal seam and shale gas is now being harvested with massive networks of collector pipelines and pumping stations, so why not methane from the permafrost? Conceivably this gas could be sold. Admittedly it would then end up as atmospheric carbon dioxide, but this would be a major net benefit to the environment. Even if it could not be transported to market but was immediately burnt, this would still be a major environmental win. Suitable financial incentives would need to be provided to the industry to do this.

Fourth, if runaway climate change is to be avoided, we must not only move to zero emissions, we must start taking carbon out of the atmosphere and returning it to long term storage underground. There is at least one way that this can be done profitably. The first step is to grow algae in very large amounts, which takes carbon out of the atmosphere. The algae are then subjected to a process called pyrolysis, which effectively turns it into charcoal. Among the by-products are gas and bio-fuel, the sale of which might well be enough to make the process profitable. This is within the capabilities of the petroleum industry. Furthermore, charcoal has agricultural value since it enhances the soil when mixed in. Very large amounts could be disposed of in this way. But the really important point from an environmental point of view is that the charcoal is relatively immune to processes of decay and will remain stored in the soil for up to a thousand year. Growing trees ties up the carbon for perhaps a hundred years, after which trees die and decay, returning their carbon to the atmosphere. Storing carbon as charcoal is far more long lasting. Again, suitable financial incentives would need to be provided.

Here is a vision that inspires me. From a climate change point of view it's hard to imagine a more depressing sight than coal trains, two and three kilometres long^x, bringing coal from the mines of inland Australia to coastal ports for shipment overseas. All of this coal is destined to end up in the atmosphere. In my imagination I see this process reversed: trainloads of charcoal produced by pyrolysing algae at coastal sites, on its way inland for burial. Is this too much to hope for? Not, I think, if the petroleum industry turns its mind to it.

These ideas will be developed in what follows. But before embarking on any of this it will be useful to understand the petroleum industry's current position on climate change.

2. The current petroleum industry position on climate change

Strange as it may seem to some, most oil and gas majors accept that climate change is both real and human-induced. More surprisingly, perhaps, they accept the need for a price on carbon to curtail human emissions.

One of the most dramatic statements to this effect was an open letter addressed to governments and the UN signed by the CEOs of six European companies in the lead up to the Paris climate conference of December, 2015. The signatory companies were Shell, BP, BG, Total, Statoil, and Eni. The letter said in part:

We call on governments, including at the UNFCCC negotiations in Paris and beyond to:

- introduce carbon pricing systems where they do not yet exist at the national or regional levels
- create an international framework that could eventually connect national systems^{xi}.

This is not an isolated statement; it is consistent with other statements emanating from these companies. For example, the chairman's message in Shell's 2014 annual report included the following statement.

One vital and pressing step is to set up effective systems for putting a price on carbon emissions. It is an efficient way to encourage companies to change their activities in ways that have a deep and lasting impact on emissions. I was encouraged to hear at the United Nations (UN) Climate Summit in New York in September 2014 that the need for effective carbon pricing systems had broad support. I hope that significant progress can be made on this at the crucial UN Climate Change Conference^{xii} in Paris in December, 2015.

What is particularly interesting about the 6-company statement above is there is no suggestion governments should wait until there is agreement on the details of an international carbon pricing mechanism. Instead it envisages national and regional initiatives that only eventually are connected. This is particularly important, given some of the more timid statements to be described below.

US companies were not among the letter's signatories, although some of them now support a price on carbon. Exxon is a case in point. For decades prior to the end of the 20th century Exxon was sowing doubt about climate change even though the company was well aware of the scientific evidence. Various agencies, and even some of Exxon's own shareholders, are now suing the company for misleading them in this respect and failing to alert them to the dangers of climate change. The potential costs to Exxon are huge. However, from the present point of view this is history, because Exxon has now aligned itself with the other major players in endorsing a price on carbon. In its 2016 report - the outlook for energy: a view to 2040 - Exxon makes the following comments.

Under a cost-of-carbon approach, the incentives for reducing greenhouse gas emissions – as well as the most cost-effective solutions – would become readily apparent. For example, in the United States it is clear that improving the fuel efficiency of conventional gasoline vehicles will reduce more emissions – at a lower cost – than expanding the use of expensive electric vehicles. Also, in the power generation sector, substituting natural gas for coal is a far more cost-effective option for curbing emissions than building new wind or solar facilities for electricity generation. By focusing on market-based solutions, governments can avoid requiring consumers and taxpayers to pay for high-cost solutions when better options abound.

What is interesting about this statement is that Exxon now sees a price on carbon as being in its interests. In particular it recognises that a price on carbon will encourage a switch from coal to natural gas – a move that directly benefits the gas industry at the expense of coal. The letter referred to earlier also explicitly recognises this as one of the benefits of pricing carbon. This is a theme to which I shall return.

Despite Exxon's position, the company does not appear to be actively lobbying governments to put a price on carbon. Indeed it explicitly refused to join with the six European oil and gas majors in their public statement exhorting governments to do so^{xiii}.

When we look at the oil and gas industry *associations* we find an exceedingly equivocal position. The peak UK body, Oil and Gas UK, made a statement following the Paris agreement of December 2015 in which it said:

Promoting greater use of natural gas in the UK energy mix and applying carbon abatement technologies at the relevant time to bear down on emissions will help the UK to meet its climate change goals and ensure the optimum balance between security of energy supply, affordability and decarbonisation.^{xiv}

There is no reference here to a putting price on carbon, despite the lead given by some of its own members in the 6-company statement. The association is well to the rear of its industry leaders in this respect.

Perhaps the most powerful association of them all, the America Petroleum Institute (API), had this to say in a statement released on the occasion of the Paris agreement.

America's energy revolution continues to deliver broad economic benefits while helping to reduce emissions of carbon dioxide (CO₂) from electricity production to near 20-year lows. These reductions are the result of market forces. They have little to do with government programs and everything to do with the fact that the United States is the world's leading producer of natural gas. With such an abundant supply of affordable fuel on hand, power plants already have an incentive to use cleaner-burning natural gas without government interference. Federal tax credits and other incentives interfere with the market and could have dire economic consequences. All energy sources have a role to play in supplying America's energy needs. But using regulatory authority to benefit one power source over another in electricity generation could stifle innovation, destroy jobs and raise energy bills for those who can least afford it.^{xv}

This statement fails to endorse the policy of pricing carbon, even implicitly; in fact it reads as a clear rejection of any such policy. This rejection flatly contradicts the position of some of API's most significant members, such as Exxon. It would be interesting to know how representative API is of its membership on this point.

Another major industry association, the Australian Petroleum Production and Exploration Association (APPEA), issued an updated climate policy following the Paris agreement^{xvi}. The two lead paragraphs of the policy are as follows.

APPEA supports a national climate change policy that delivers greenhouse gas emissions reduction at least cost and facilitates broadly-based investment decisions consistent with an international price on carbon.

Climate policy must be fully integrated and consistent with policies in other areas – including energy, international trade, taxation, economic growth, population and environmental and social responsibility.

This is a remarkable statement that deserves close scrutiny. It is far from a ringing endorsement of the policy of putting price on carbon. Instead it endorses a climate policy that is *consistent with* an international price on carbon. Moreover, it appears to *discourage* Australia from going it alone, since it speaks of an international price on carbon. Finally, the second paragraph suggests that APPEA would oppose a price on

carbon unless it was fully consistent with large range of other priorities. This is an almost impossible condition to meet. Imposing this condition downgrades climate change to just one of many considerations and certainly not the most important one.

The APPEA climate change policy lists the four principles:

1. international engagement is crucial;
2. climate change and energy policies must be integrated and harmonised;
3. climate change adaptation policies are necessary;
4. climate change policy must not compromise national or global economic development or energy security.

Point 2 is elaborated as follows.

“Australia’s policy response should seek to:

- Deliver lowest cost greenhouse gas emissions abatement through an appropriately designed mechanism that provides an economy-wide transparent price signal to shape business and consumer plans and investments. The mechanism should be efficient, have low compliance costs, and support international trade that recognises different national circumstances....”

This statement indeed supports a “price signal”, but that support is so heavily qualified that it is again equivalent to opposing a price on carbon unless certain conditions are met.

We can get an insight into APPEA’s position by looking at its response to a particular proposal to put a price on carbon. This was the 2011 Labor government proposal to tax emissions from several hundred^{xvii} of the biggest carbon emitters in Australia. Among the facilities covered were processing plants producing liquid natural gas (LNG) for overseas markets. The tax would only apply to the emissions generated in the production process, not to emissions generated by end point gas users in other countries. APPEA’s response was that industry should be exempt from the tax because it would damage international competitiveness^{xviii}. Industry experts said, however, that although the carbon tax would erode the profit margins of some LNG projects, no major projects will become uneconomic as a result of the tax^{xix}. The conservative parliamentary opposition opposed the carbon tax and the shadow minister for energy added his voice to APPEA’s, saying that

“anything that diminishes the world’s ability to produce LNG and use it as an alternative fuel to coal fired power stations is nothing short of environmental vandalism ...^{xx}

Even the CEOs of some of the companies concerned joined the campaign to have LNG exempted from the carbon tax^{xxi}.

The campaign was a partial success, with the government agreeing to exempt the industry, at least initially, from two thirds of the tax it would otherwise pay.^{xxii} When the conservatives came to power in 2014 the tax was rapidly repealed, with APPEA expressing its pleasure that a “cost burden” had been removed from LNG exporters^{xxiii}.

Australia’s experience with a carbon tax makes it clear that APPEA will strenuously oppose placing a price on carbon for LNG producers for the foreseeable future. The 2015 Paris agreement contained no legally binding provisions of this nature and a world-wide binding agreement on pricing carbon is still a long way off.

THE COAL INDUSTRY POSITION ON PRICING CARBON

One might imagine that of all industries, the coal industry would be the one to hold out longest against the reality of human-induced climate change and against the need for a price on carbon. It is instructive therefore to review the coal industry position.

In fact, neither the industry associations nor individual coal companies deny the significance of climate change. Furthermore, there is universal agreement that action on climate change is needed.

But as far as most coal industry associations are concerned carbon pricing is not part of the solution^{xxiv}. Their websites are generally silent on this issue, but their opposition is vehement when it comes to the point. When Australia was planning to introduce its carbon tax in 2011, a coal industry spokesman claimed that

Thousands of jobs and billions of dollars of investment in coal mines and related businesses are at risk from the carbon tax^{xxv}.

And when the tax was repealed, the mining industry was ecstatic. According to one industry body,

“one of Australia’s biggest public policy mistakes in decades has been fittingly consigned to the dustbin with today’s repeal of the carbon tax legislation”^{xxvi}.

The industry attitude is that new technologies will provide a low emissions future for coal, without the need for carbon pricing. Two technologies in particular are mentioned. First, a new generation of High Efficiency Low Emissions (HELE) power stations will substantially cut CO₂ emissions, and secondly, the technology of carbon

capture and storage (CCS) will allow large quantities of CO₂ to be stored permanently underground. Coal industry discussions of climate change invariably devote a great deal of attention to these ideas. The assumption that these technologies will secure a bright future for coal seems wildly optimistic, but to discuss this here would take us too far afield.

We can also locate coal mining in a broader context. The largest coal mining companies along with various coal associations belong to an umbrella association - the International Council on Mining and Metals (ICMM). Perhaps because of its broader vantage point this council envisages putting a price on carbon.

Here is an extract from its position statement on climate change^{xxvii}

- We support an effective binding global agreement on climate change.
- We support a price on carbon, and other market mechanisms that drive reduction of greenhouse gas emissions and incentivise innovation.
- We recognise the need to reduce emissions from the use of coal, and support collaborative approaches to accelerate the use of low-emission coal technologies as part of a measured transition to a lower-emissions energy mix. That transition should recognise the importance of coal in the global economy, and particularly in the developing world.
- We support greater use of renewable energy and other cost effective low-emission technologies, and improved energy efficiency, including in our own operations.

As for individual mining companies the situation is quite varied. Here is what one of the largest, Anglo American, has to say in its position statement on climate change^{xxviii}. It supports, among other things

- the use of fair and well-designed market-based instruments, such as carbon pricing;
- greater provision of public-private funding for research and development and for the deployment of CCS, and carbon capture and reuse (CCR) technologies;
- treatment of CCS on a comparable basis to other technologies that abate carbon emissions.

The first of these points is at first sight surprising, but Anglo American is a member of the ICMM and has endorsed the ICMM statement quoted above^{xxix}. However there is still plenty of scope for the company to object to any particular price scheme on the grounds that it is not “fair” or “well-designed”.

The emphasis on carbon capture and storage in the second two dot points demonstrates just how important this technology is to the future of coal, in the company's view. It expands on this in its sustainable development report of 2014:

We believe that the roadmap to reduced CO₂ emissions from coal-fired power generation involves two steps: first, more efficient coal combustion and, secondly, in the longer term, the deployment of carbon capture and storage technologies. Replacing the world's inefficient coal plants with existing ultra-supercritical combustion technology would cut carbon emissions by the equivalent of India's entire current carbon emissions...

One can infer from these various statements that in Anglo American's view the coal industry will only be able to survive a carbon pricing regime if certain conditions are met. Those conditions are that existing coal fired power stations are replaced with far more efficient ones, and that the CO₂ produced from these power stations can be captured, transported and stored securely underground.

In fact Anglo American seems to have little faith that the above conditions will be met. The company announced in early 2016 that it intended to divest itself of its coal business.

The Group's Coal assets have been identified as non-core and will continue to be actively managed for further performance improvement, with a view to making appropriate divestment decisions over time^{xxx}.

This is hardly a vote of confidence in the future of the coal industry.

To complete the picture, Anglo American's position on climate change also calls for it to progressively reduce direct emissions from its operation –its own carbon footprint - as opposed to the emissions from the consumers of its coal.

At the other end of the scale, consider one of the smaller coal mining companies in Australia – Centennial. The section of its annual report addressed to climate change devotes a great deal of attention to the company's efforts to reduce carbon dioxide and methane emissions from its mine sites, but expresses no view on the desirability or otherwise of pricing carbon. It does however say that "the key challenge with respect to climate change remains the uncertainty with respect to domestic carbon policy."^{xxxi}

In summary, individual coal mining companies do not necessarily back their industry associations, at least not publically, in the strong stand against carbon pricing taken by some of those associations. It goes almost without saying that whether or not

individual coal companies explicitly oppose a price on carbon, we cannot expect to see them lobbying actively for such policy.

PORTFOLIO COMPANIES

Anglo-American is not just a coal mining company. It is better described as a diversified miner, producing a variety of other minerals apart from coal. It describes its decision to divest its coal business as “transforming its portfolio”. While it does not explicitly link its decision to climate change, other diversified commodity companies do envisage this strategy as a response to carbon pricing.

Consider BHP Billiton, which has large petroleum and coal divisions, as well as iron ore, copper and uranium businesses. As already noted, its coal business has an interest in avoiding any price on carbon, but its gas business stands to benefit from such a price. So where does the company as a whole stand?

BHPB’s position has long been that it can live with a price on carbon. Indeed it has been assuming a price on carbon in making investment decisions since 2004. Its present position goes beyond this, in that it endorses a price on carbon^{xxxii}. If and when a price on carbon begins to bite, the strategy will be to adjust its portfolio of assets, so as to maximise return on investment. BHPB lays out that strategy as follows.

Our analysis shows that the portfolio is resilient due to long-term demand, high-quality resources, low production costs and rapid payback periods of growth projects. In a 2°C world, we believe there is a likelihood of upside for uranium, high-quality metallurgical coal and iron ore.

In addition, we expect that copper is resilient and would offer continued opportunity for growth. The Company’s gas exposure may also provide significant opportunities during a transition to a lower emissions economy although in the long run, emissions from the use of natural gas will also need to decline. In aggregate, we anticipate these commodities are robust and mitigate potential negative impacts on other commodities.

Depending on the speed of transition and the energy choices made, we will have opportunities to mitigate the impacts on the value of our portfolio through selectively investing in the commodities that will benefit from structural market changes.

Thermal coal, used for coal fired power stations, is not explicitly mentioned in this passage. However the statement does refer to “potential negative impacts on other commodities”, which is implicit recognition that BHPB’s thermal coal business will

shrink under a carbon pricing regime. But the important point is that when carbon pricing begins to bite, BHPB's strategy is simply to rebalance its portfolio. It is this rebalancing strategy that enables it to view a carbon pricing regime with such equanimity.

SUMMING UP

To sum up, climate change denial is a thing of the past in the petroleum industry, and even for the coal industry. All public statements acknowledge the reality of human-induced climate change and the need to move to a low carbon future. But that is where agreement ends. The petroleum industry associations vary in the extent to which they regard carbon pricing as desirable, but none of them is actively advocating such a price. Moreover, if the Australian experience is anything to go by, they can be expected to lobby against the imposition of carbon pricing when the opportunity arises. Individual company attitudes vary quite considerably.

Leading European petroleum companies advocate the progressive extension of pricing regimes, without waiting for complete international agreement, while others are far more reluctant to go down this path unless there are universal binding agreements.

What is perhaps most interesting from the present point of view is that there is not a great deal of difference in the public statements about carbon pricing between the coal and the petroleum industry. The gas industry sees a bright future for itself in the short term, at the expense of coal. Moreover, the transition from coal to gas can only be hastened by a carbon price. One might have expected that the petroleum industry would therefore be distinctly more receptive to the idea of pricing carbon than is the coal industry. To date, that does not seem to have been the case.

3. Why the petroleum industry should advocate a price on carbon

The petroleum industry accepts the reality of man-made climate change and the need to do something about it. So what can the industry do? The first and most obvious strategy is to provide active, not merely passive support to pricing carbon. This means lobbying for an effective price, one that really will drive change, and one that in particular will help make coal uneconomic vis a vis gas, and of course renewables. Renewables will eventually replace gas as well, but there is a window of opportunity for gas to replace coal, before that happens. A price on carbon will also provide other important opportunities for the gas industry which I shall address in later sections.

REPLACING COAL WITH GAS

We should begin by noting that even in the absence of a price on carbon, gas is increasing its market share vis a vis coal. This is happening in two of the biggest greenhouse gas emitting countries - the US and China.

In the US, two factor factors are at work. First, the discovery of new sources of gas in recent years has resulted in a sustained reduction in gas prices. Second, more stringent environmental regulations have been implemented to combat the locally polluting effects of coal burning. These make it more difficult for coal fired power stations to remain in business.

To elaborate this last point, there are at least three ways that coal burning utilities can respond to more stringent environmental regulations: installing costly pollution control equipment; closing old power stations and replacing them with new generating capacity; and modifying existing power stations to burn gas rather than coal. This last option has proved attractive in the US where a slew of old coal burning power stations have been converted to gas, in response to tougher anti-pollution regulations and the reduced price of gas^{xxxiii}.

In China, the local pollution problem in cities is so serious it is now a major health issue and an embarrassment for government^{xxxiv}. This is driving a rapid turn away from coal to clean and cleaner fuels. For example, China is leading the world in wind power generation. It is also expanding its gas fuelled power generation as a way meeting the demand for power while at the same time reducing reliance on coal fired power stations. China had been planning to build many more coal fired power stations, but in

2016 it reversed this policy and has all but banned new coal fired power stations. It has also announced that the last four coal fired power stations in Beijing will be replaced by gas in 2017.^{xxxv}

In short, a move from coal to gas is already underway in some places, for reasons that have nothing to do with pricing carbon. A carbon price can be expected to initiate this trend, where it is not already underway, and to accelerate it, where it is.

ENVIRONMENTALIST CONCERNS ABOUT REPLACING COAL WITH GAS

What is so attractive about replacing coal with gas, even if only for a relatively brief “transition” period until renewables have caught up, is that this is a win/win for the gas industry and for the climate. It is obviously a win for the gas industry during the transition to renewables, but it is more controversial to claim that this is beneficial from a climate change point of view. Environmentalists argue that gas is part of the problem, so how can it be also part of the solution? Electricity from wind and solar powered generators is already competitive with electricity from new coal or gas fired power stations. From an environmental point of view, society would therefore be better off promoting the uptake of renewables, rather than encouraging a switch from coal to gas fired power generation.

The answer is that, from a societal point of view, a price on carbon is not *intended* to encourage switch from coal to gas. It is intended to reduce the quantity of greenhouse gases emitted into the atmosphere. If one of the consequences of putting a price on carbon is to initiate or accelerate a switch from coal to gas, this is the market working as it was designed to work. In the longer run gas will no doubt be replaced by renewables, because eventually this will make economic sense, either because of the falling price of installing new renewable generating capacity and/or because of the increasing price placed on carbon.

In some quarters there is a concern that if government policy encourages the construction of new and more efficient gas fired power stations^{xxxvi} in place of existing coal fired stations, this will have a detrimental longer term effect on emissions, because such stations will have a life time that extends beyond that of the coal fired power stations they replace^{xxxvii}. However a steadily rising carbon price and/or the steady fall in the cost of building renewable energy generating capacity, means these new gas fired plants will be replaced by renewable power as soon as it is economically sensible to do so, and possibly long before their normal life time has expired. In other words, these new gas fired plants may end up stranded before they come to the end of

their normal life. Investors will therefore need to think carefully about payback periods before investing in new gas fired power stations^{xxxviii}.

Converting existing coal fired power stations to gas is another matter. Converting a coal fired boiler to run on gas is not nearly as costly as building a new gas fired boiler^{xxxix}, so the pay-back period is much less^{xl}. Moreover it does not extend the life of an existing power station by the lifetime of a new gas fired power station. It is more truly an interim measure until renewables catch up.

It is also possible to accelerate the move to renewables by more interventionist policies such as setting energy retailers mandatory renewable energy targets. Such policies are in place in many countries but they do not of course address emissions from other sources such as the manufacturing sector, or methane emissions produced by ventilation systems in coal mines. If we restrict attention to the energy sector, renewable energy targets are indeed promoting a reduction in carbon emissions, just as would a price on carbon. The difference between the two policies, in the energy sector, is that renewable energy targets do not serve the immediate interests of the gas industry in the way that a price on carbon does by driving up the price of coal fired power relative to gas. It follows that it is in the interests of the gas industry to promote a price on carbon rather than renewable energy targets, where that choice is open.

In the US, the Obama administration developed a clean power plan which in effect involves renewable energy targets^{xli}. At the time of writing the plan is on hold because of a legal challenge by a number of state governments. It is noteworthy, though, that the plan gives states an opportunity to meet some of their targets by replacing coal with gas. However there are significant restrictions on this option, aimed at “limiting the rush to gas”, as it is called.^{xlii} Such administratively imposed restrictions would not exist under a carbon pricing scheme. Again, therefore the gas industry would probably have been better off lobbying for a carbon pricing scheme, if that had been an option^{xliii}.

PARTING COMPANY WITH COAL

If the petroleum industry were to lobby for a price on carbon in the hope of driving coal out of business, this would amount to a public parting of the ways with that industry. This may be uncomfortable for petroleum industry, given that the resource industries often like to present a united front for political purposes.

Nevertheless, a few months before the Paris conference, the CEO of Australia’s largest petroleum company, Woodside, set off down this path with a speech at a world gas conference, also in Paris. Coal was not only much worse than natural gas from global

warming point of view, he said, it was also producing devastating local atmospheric pollution in the big cities of China and India. The world had to look to a combination of natural gas and renewables as it moved to a lower carbon future. Here are his words:

"Our industry has historically been too timid to address the shortcomings of coal but now it's time for us to stand up and we need to stand united. ... We, the gas sector, must do more to highlight the benefits of gas over the product of our competitors."

As for clean coal, "give me a break", he said. "Who coined 'clean coal' and why did we let that happen"^{xliv}.

The reaction in Australia was intense. According to the CEO of Whitehaven Coal, coal and gas were "complementary" in providing "energy for the masses", not antagonistic^{xlv}. Many petroleum industry executives felt uncomfortable about the comments of the Woodside CEO and a spokesman for the industry association, APPEA, pointedly failed to endorse his attack on coal^{xlvi}. One executive worried that the words of the Woodside CEO had put him at odds with the then Prime Minister, Tony Abbott, who famously declared coal "good for humanity". Another executive said:

"I cannot see why [the CEO] has created this division...There are other things to focus on. It's not one form of energy over another; it's about how we reduce carbon dioxide emissions and improve energy efficiency. It should be a technology-neutral debate"^{xlvii}.

Finally, a former senior executive of Woodside and former federal resources minister went on record as saying:

"It is not wise for companies or their leaders to wage war on any one energy source, or talk down the prospects of one source of Australia exports."

Clearly the petroleum industry, and even some of the politicians who represent it, are not comfortable with acknowledging that the coal and gas industries have divergent interests. It will take courage on the part of the gas industry therefore to advocate actively a price on carbon, in the expectation that this will increase market share vis a vis coal. Some petroleum industry leaders are not afraid to pursue this line.

ENERGY COMPANIES

The politics of replacing coal with gas has another dimension, because the interests of energy retailers align with the gas industry more than with the coal industry. Nowadays energy retailers are often large integrated energy companies covering both

retailing and power generation. In Australia a large majority of the most polluting coal fired power stations are owned by energy retailers, but none of these companies produces coal for sale. They all have significant portfolios of renewable energy, in part driven by Australia's renewable energy target. Interestingly, two of the largest energy retailers, Origin and AGL, produce natural gas. Clearly if the carbon price is right they will switch from coal to gas fired generation without much urging. Indeed Origin has said:

“Australia’s 2030 target will require a significant transformation of the energy sector. Given Origin’s track record in renewables and strategic interest in gas-fired generation, we’re ready and willing to lead the response”^{xlviii}.

After the Paris agreement the CEO of Origin said

“There is [now] a greater global resolve- and we will need more gas and more renewables to achieve it, and less coal”^{xlix}.

There should be ways in which petroleum companies can develop political alliances with these energy companies to encourage a price on carbon that will help gas take market share from coal.

For example, the four most polluting coal-fired power stations in Australia are concentrated in a particular area of the state of Victoria. All burn brown coal and all are owned by energy companies. If this cluster of power stations could be converted to gas, this would be an enormous boost to the environment movement, and a big win for the gas industry. Perhaps the strategy of the petroleum industry should be to have a sufficiently high price placed on carbon to make this an economic proposition.

SOLAR THERMAL

But just as gas can replace coal by direct conversion of existing power stations, solar may also be able to replace gas in a similar way. How might this happen?

Conventional coal-fired power stations burn coal to heat the boilers that produce the steam that drives steam turbines that generate electricity. The simplest way of converting coal to gas fired generation is to modify only the first step in this chain, that is, to heat the boilers using gas rather than coal.

Solar energy can also be used to produce the steam that drives the turbines. One way to do this is to construct a large field of mirrors, arrayed around a tower, which focus the sun's rays to the top of the tower. The resultant heat energy is used to heat a transfer fluid which is piped to the power station to create steam. The mirror field

needs to be 2 or 3 square kilometre and the tower needs to be within about 3 kilometres of the power station to make it economically viable. Such a scheme has been proposed for coal fired power stations at Port Augusta in South Australia. Could it be that the window of opportunity for converting coal to gas fired power stations has now closed?

The answer appears to be: not yet. A careful study in the Port Augusta case found that the proposal could not be justified on economic grounds.¹ The study also highlights the fact that it may not be easy to find several square kilometres of land for a mirror field close to an existing power station.

Just to complete the picture, new solar thermal power stations are already being built in some parts of the world and will eventually contribute to the demise of fossil fuels.

4. Reducing methane emissions

Reducing methane gas emissions is a second potentially win/win strategy - financially advantageous to the petroleum industry and hugely beneficial for the environment. Methane is a greenhouse gas far more potent than carbon dioxide. Once released into the atmosphere it is 80 to 100 times more effective at trapping heat than carbon dioxide, for perhaps the first 20 years. However it tends to break down over time to carbon dioxide, so that after 100 years its capacity to trap heat is only about 25 times greater than carbon dioxide. The 20 year time frame is more relevant in the present context since this is the period when our fate will be determined. The 80 to 100 multiplier is therefore the most relevant one^{li}. Regardless of what figure is used, the atmosphere is far more sensitive to methane emissions than carbon dioxide and the problem of methane emissions is now firmly on the scientific agenda. Reducing methane emissions will not only be beneficial to the environment; but as I hope to show, it benefits the gas industry as well.

In this section I shall deal with a number of distinctly different methane emission sources. All are directly attributable to the activities of the petroleum industry - pipeline leaks, underground gas storage failures, and coal seam and shale gas production. In the following section I deal with a methane release that is not attributable to the petroleum industry - the release of methane that is occurring as the permafrost melts in Arctic regions. This is perhaps the most serious of all sources of atmospheric methane, the one that will do the most damage to the environment.

SUPPLY CHAIN LEAKAGE

Recent years have seen the rapid expansion gas production from unconventional sources, such as shale gas in the US, and coal seam gas in Australia. The expansion of shale gas in the US has been particularly dramatic, driving down the price of gas in that country to new and stable lows. Indeed some have called this the golden age of gas. Others have worried that cheap new gas may “stop renewables in their tracks”, unless governments stick to their renewable support schemes, such as pricing carbon^{lii}. However the steadily falling price of renewables, coupled with the fact that many governments are indeed committed to providing incentives for renewables, means that this worry is diminishing.

Section 3 of this paper raised the prospect that gas might be a temporary bridge to a low carbon future. This idea depends critically on the assumption that fugitive

emissions of methane – leaks – are insignificant. However research is now indicating that fugitive emissions in the production and transmission of gas are indeed significant and may even cancel out the advantage of burning gas rather than coal. If this turns out to be the case the gas industry will be under increasing pressure to curtail these emissions, if it wishes to maintain its claim to be part of the solution rather than the problem.

Moreover, if fugitive emissions are included in carbon accounting, a policy of pricing carbon will not deliver the benefits to the gas industry discussed in the last chapter, unless such emissions can be substantially curtailed. It is therefore in the industry’s interests to fix this problem.

The issue of fugitive emissions has been linked to hydraulic fracturing - better known as fracking - the technique by which gas is released from shale beds, and to a lesser extent, coal seams. Fracking involves pumping water, chemicals and sand under high pressure down into the shale beds so as to fracture them, thus releasing the trapped gas. There are several potentially damaging consequences of fracking - for example the contamination of underground water sources (aquifers), and the tendency to cause earthquakes - which will not concern us now. The issue of interest here is the seepage of methane into the atmosphere to which fracking gives rise.

It is noteworthy that the fugitive emissions from Australian coal seam gas (CSG) well sites are about one twentieth the emissions from shale gas well sites in the US^{liii}. One possible reason for this is that while fracking is always necessary to release gas from shale, this is not true for CSG. In one CSG field in Australia, fracking has been used for only 10% of wells^{liv}. More generally fracking may be necessary in up to 50% of CSG wells.^{lv}

However it is not clear to what extent fracking itself is the source of methane emissions in shale gas wells in the US. Measurements are usually of methane leakage from a site, which can stem from the fracking process or from leaky pipes, joints and valves on site. Moreover there are other sources of emission downstream from the well sites. The US Environmental Protection Agency (EPA) has made the following estimates of the distribution of methane leakage.

Drilling and fracturing	0.2%
Production	0.4%
Processing	0.2%
Transportation and distribution	0.7%
Total leakage	1.5%

These figures are percentages of gas produced^{lvi}. End users are not included in this analysis and they can be expected to increase the total leakage rate.

The table is included here to give an indication of the relative importance of leakage at the stage of drilling and fracturing; the figure of 0.2% represents only 13% of the total losses in the system (0.2 as a percentage of 1.5). In fact the sources of leakage throughout the system are many and varied, including leaking valves and flanges, rusty pipes, compressors and pumps. As one knowledgeable commentator titled his article: "It's Not Fracking [We Need] to be Concerned with, It's a Fugitive Hiding Along the Supply Chain that is A Clear and Present Danger"^{lvii}.

The figure of 1.5% used by the EPA for total system losses in the above table is conservative. In another context the EPA has estimated the leakage rate at 2.9%. A study by Cornell University researchers put the figure at 3.2%^{lviii}, but this study has been subject to withering critiques. Other studies put the figure significantly higher. Coincidentally a separate and independent study has estimated that a leakage rate of 3.2% is exactly enough to cancel out the greenhouse gas benefits of moving from coal to gas.

In the UK, a 1990 study found that between 5.3 and 10.8 % of gas flowing through Britain's natural gas pipelines was leaking. The study also calculated that a leakage of 2.8 percent would cancel any greenhouse gas advantage of natural gas over fossil fuels like oil and coal^{lix}.

Clearly, more research is needed before drawing any conclusions about overall leakage rates and about whether these cancel out the presumed benefits of gas. Moreover, there is one additional matter that should be taken into account. A significant proportion of the leakage in the system is taking place from the distribution pipelines in urban environments. Some of these pipelines are many decades, if not centuries, old. And the older they are, the more they leak. However this leakage is hardly relevant here, because the proposed gas fired power stations would probably not be situated at the end of these aged and leaky lines. What is relevant in the present context is the leakage from the well head and along the major gas lines to the power stations, and it is this additional leakage that must be taken into account in determining whether fugitive emissions outweigh the presumed advantages of converting from coal to gas. To conclude, more research is needed, but in view of all the uncertainties it is obviously in the interest of the gas industry to take strenuous steps to reduce the rate of leakage from the system.

In summary, reducing methane leakage from the gas supply chain is a win/win for the environment and the gas industry. It is obviously beneficial from a climate point of view because methane is so much worse than carbon dioxide as a greenhouse gas. It is

a win for the gas industry because methane leakage potentially undermines the claim that gas is better than coal for the environment; minimising such leakage enables the industry to maintain that claim.

URBAN GAS PIPELINE LEAKAGE

As noted above, gas distribution pipelines in urban areas can be a particularly leaky part of the total gas supply chain. Transmission lines bring gas to the “city gate” under very high pressure. City gate stations then reduce the pressure and send the gas through a network of distribution pipelines to the end user. The opportunities for leakage in these urban systems are widespread, especially in cities where the network of pipes has been in operation for many decades or even a century or more. The densely populated cities of eastern United States have thousands of such leaks^{lx}. The situation is similar in Australia^{lxi}. It is therefore worth considering this problem in more detail.

A recent study in the city of Boston is very helpful in the respect^{lxii}. The study identified leaks from urban pipelines based on methane monitoring along pipeline routes. It selected 100 leaks for closer examination. It found that most of the leakage was coming from a small number of leaks, which could be described as “super-emitters”. In fact 7% of the leaks in the study accounted for 50% of the leakage^{lxiii}. Such a finding has important implications. It means that big reductions in total leakage can be achieved by identifying and fixing a relatively small number of super-emitters.

Moreover, taking such steps is beneficial to the gas industry from a narrow cost/benefit perspective. It has been estimated that Boston loses about 2.7% of its natural gas to leakage each year. This amounts to an annual loss of \$90 million^{lxiv}. Selling the gas which would otherwise be lost is a significant revenue source that offsets to varying degrees the cost of abatement measures. In fact there are many abatement measures where the revenue generated is equal to or exceeds the costs, making it profitable to install the abatement measures. However regulatory changes may be necessary to ensure that the abaters get the benefit of the additional gas revenue, thus providing them with the necessary incentive.^{lxv}

If the concentration of methane in the atmosphere reaches 5% it is flammable and potentially explosive in a confined space. Moreover, explosions and fires stemming from gas leakages in urban areas are not uncommon. The Boston study noted that in a recent five year period in the state of Massachusetts (of which Boston is the largest city), there had been 23 distribution pipeline incidents resulting in 1 fatality, 18 injuries and \$6m of property damage. The study found that a massive 15% of the 100 leaks it

examined were potentially explosive, and they reported these cases immediately to the authorities. However, large leaks were no more likely to be explosive than small leaks, and so a policy of concentrating on super-emitters does not have the same disproportionate benefits for safety as it does for the environment. Safety depends on reducing the number of small leaks as well. Nevertheless, reducing the number of super-emitters does have a safety payoff, which from the present point of view is an unexpected bonus.

In summary, fixing the super-emitters would be highly cost-effective, resulting in significant net financial savings. Here again, methane abatement is a win/win strategy – beneficial for the environment and financially advantageous to the industry and its customers.

CATASTROPHIC STORAGE FAILURES

The reliability of gas supply depends on the existence of gas storage so that peak demand in winter can be met without placing unmanageable demands on the supply system. In many parts of the world this storage takes the form of depleted underground oil and gas reservoirs. In the US, for instance, there are 418 such underground storage facilities^{lxvi}. In Australia there are approximately half a dozen underground storage facilities^{lxvii}.

A catastrophic failure of one of these storage facilities results in major economic loss and a major release of methane into the environment. There is also the risk of explosion and loss of life.

The issue is highlighted by the recent experience of SoCalGas (South California Gas). The company owns one of the largest reservoirs in the US, the Aliso Canyon Storage Facility, located on the outskirts of Los Angeles. In October 2015 the reservoir blew out, allowing 1,200 tons of natural gas to spew into the atmosphere every day^{lxviii}. The blowout occurred with the force of a volcanic eruption and if it had ignited it would have been impossible to extinguish. Low flying aircraft were diverted from the area so as to remove potential ignition sources and work at the site was prohibited at night to prevent lights igniting the gas^{lxix}. In retrospect it seems like a miracle that no ignition occurred. Previous leaks from underground storage facilities in the US have indeed ignited, causing explosions and death^{lxx}.

- In January 2001, natural gas escaped from underground storage in rural Kansas, causing explosions and fires that destroyed buildings and killed two people.
- In August 2004, a damaged well at an underground gas reservoir 40 miles northeast of Houston caused explosions that shot flames 1,000 feet into the

air. The leak forced residents living within three miles to evacuate and between \$30 and \$40 million worth of gas was lost.

In the Aliso Canyon case there was no ignition, but several thousand nearby households^{lxxi} were forced to relocate to temporary accommodation and there were widespread complaints from residents about health effects from exposure to the gas. In particular, of 600 households the registered complaints, a third reported nosebleeds^{lxxii}.

The initial release rate from the well represented 25% of California's daily methane emissions,^{lxxiii} although this rate declined as the pressure in the reservoir dropped. It has been estimated that the daily rate of methane release had an impact on the environment equivalent to the daily emissions of 6 coal fired power stations.^{lxxiv} The blowout was finally plugged three and half months after it began, by which time it had released over 100,000 tons of gas, mainly methane, into the atmosphere. This made it the biggest single methane release in US history.^{lxxv} Such a massive injection of methane into the atmosphere played havoc with the state's methane reduction target and seriously embarrassed the state's governor, who had made reduction of greenhouse gases one of his signature issues^{lxxvi}. In response, the governor ordered the company to pay for a mitigation program that would fully offset the climate impact of the blowout^{lxxvii}. This represents a dramatic new risk for gas companies - in future they are likely to be held accountable not only for the immediate cost of a major release, whether ignited or unignited, but also for the longer term global warming impact of the release. Because of the way such incidents will be viewed in future, petroleum companies now have an additional interest in preventing them – an interest which they share with the environment movement.

The Aliso Canyon blowout has often been compared to the Deepwater Horizon blowout in the Gulf of Mexico in 2010. That blowout cost 11 lives and did enormous damage to the economies of the states where the spilled oil reached shore^{lxxviii}. Compensation payouts amounted to tens of billions of dollars. In contrast, the Aliso Canyon blowout caused little local damage and the compensation payouts will be tiny in comparison to the Deepwater Horizon. But environmentalists argue that the damage to the climate caused by Aliso Canyon blowout is much worse than that caused by the Deepwater Horizon accident.

The Aliso Canyon release resulted from the failure of a well running thousands of feet down into the reservoir, which allowed highly pressurized gas to flow back to the surface and into the atmosphere^{lxxix}. The well was originally drilled in 1953 to extract oil from the reservoir. Over a hundred such wells were drilled. "The well initially had a safety valve, which was removed in 1979 because it was old and leaking. Because the

well was not considered critical, that is, within 100 feet of a road or a park, or within 300 feet of a home, the valve was merely removed and not replaced".^{lxxx} No investigative report has been released at the time of writing so it is not clear whether the absence of this valve was a critical factor.^{lxxxii} However the Aliso Canyon disaster revealed that underground storage facilities in the US were not effectively regulated. New regulatory rules are being developed, but critics argue that they do nothing to prevent what happened at Aliso Canyon from happening again.^{lxxxii}

Major blowouts from gas storage facilities are a very different phenomenon to the fugitive emissions that occur all along the gas supply chain. The latter are on-going, routine and measurable, giving rise to predictable annual financial losses. Moreover there are well known and cost-effective ways to reduce these fugitive emissions. In contrast, blowouts from gas storage facilities are relatively rare. They are unexpected and accidental events. This is not to say they are unpreventable - courts often find subsequently that such accidents result from corporate negligence and were readily preventable. But the rarity and accidental nature of these events puts them in different category from more mundane fugitive emissions. A different approach is therefore needed.

The key to this different approach is to think of such events not merely as environmental problems but also as *process safety incidents*. A process safety incident involves a loss of control of a process and the escape of dangerous substances from the pipes, tanks and wells in which they are normally contained (loss of containment). The term *process safety incident* is now in widespread use to describe incidents such as the Deepwater Horizon blowout. Had the release at Aliso Canyon ignited, it would have been treated as a failure of process safety, not just as the environmental disaster it undoubtedly was. But it makes perfect sense to treat it as a process safety failure, even though there was no ignition.

Thinking of the Aliso Canyon release as a process safety failure provides important insights into the prevention of such releases. In the field of safety it is now understood that high frequency low severity incidents, such as individual injuries, are very different from low frequency high consequence events such as fires and explosions, and that preventing these different kinds of events requires different strategies^{lxxxiii}. The same is true for environmental events – low frequency high consequence events require a response that is rather different from the kind of response appropriate to high frequency relatively low consequence events such as routine fugitive emissions.

Moreover the rarity of major process safety incidents means that organisations get away with careless and inadequate practices for long periods of time without negative consequence. The absence of any incident is taken as an indicator of the adequacy of

incident prevention strategies, when in fact there may be deep-seated flaws in the way things are being done that will result in disaster as soon as the relevant circumstances arise. A classic example in the Australian context is the Exxon gas plant accident at Longford near Melbourne in 1998.^{lxxxiv}

The prevention of process safety incidents requires that operators carefully analyse the ways in which they could occur, then put in place controls or defences against their occurrence, and finally monitor those controls carefully to ensure that are working as intended. Some of these controls may be specifically required by regulation, others may not be. But operators must be willing to back their own expert analyses and install controls they judge to be necessary, even where they are not specifically required by regulation.

Prevention of process safety accidents depends on being constantly mindful of their possibility. That was not SoCalGas's approach. Its aim was to comply with relevant regulatory rules, and it implicitly assumed that this would safeguard it against disaster^{lxxxv}. I have characterised this elsewhere as the "compliance is enough mentality"^{lxxxvi}. The fact is that mere compliance is never enough. Companies must go beyond compliance, particularly where the regulatory regime is as inadequate as it has been for gas storage facilities in the US. They must adopt a true risk management approach which requires that they evaluate the risks carefully and ensure that they have reduced the risk to "as low as reasonably practicable", to use a term that is familiar in countries that follow the UK legal system, or "to the extent feasible", a term that is beginning to be heard in relation to the petroleum industry in the US.

The implication of all this is as follows. Incidents like the Aliso Canyon disaster are obviously detrimental from a climate change point of view. They are also detrimental to the petroleum industry because they raise doubts about whether gas can reasonably claim to be a bridge to a low carbon future. The way for the industry to reduce the risk of such accidents is to ensure that companies adopt best practice risk management strategies which go well beyond most regulatory requirements in the US. I have argued elsewhere that the most appropriate way for regulators to deal with process safety or major hazard risk is by implementing safety case regimes, which embody the risk identification, control and monitoring approach sketched above, but to embark on that topic now would take us too far afield. Suffice to say that it is in everyone's interest that the risk of major methane gas blowouts be effectively controlled.

5. Capturing Permafrost Releases

Stopping climate change is not just a matter of reducing our emissions, even to zero. The problem is that there are natural amplifiers or accelerators at work, which mean that the degree of warming the world has already experienced may already have triggered runaway change - unless of course we can find a way to interrupt those natural amplifiers. Ironically the gas industry is particularly well placed to do this. Indeed it has the potential to make a major contribution to saving the planet as we know it.

CRYOSPHERE AMPLIFIERS

While politicians at the Paris climate conference were celebrating the success of their negotiations, a group of climate scientists at one of the many conference side meetings, was stressing the urgency of much greater emissions cuts. They were releasing their report on the state of the *cryosphere* – the polar and alpine regions of snow, ice and frozen ground. The report, ominously titled, *Thresholds and Closing Windows*,^{lxxxvii} argues that changes are occurring in these regions that are largely irreversible on human time scales.

The reason scientists are so concerned is because of what they called the “polar amplification”, which occurs particularly in the Arctic. Polar regions are warming twice as fast as the rest of the globe^{lxxxviii}, which makes these amplification processes even more significant.

There are several processes involved. The first concerns Arctic sea ice. The area of sea ice grows each winter and shrinks each summer, but in recent decades the limit of summer sea ice has rapidly retreated northwards, and it is predicted that on current trends the Arctic Ocean will be free of ice each summer by about mid-century. Now here’s the catch. Summer sea ice reflects most of the sun’s energy that falls on it, while open water absorbs most of it. So, the more exposed water there is during the summer, the more solar energy is absorbed and the greater the warming. It’s a vicious cycle that will only be broken if the planet can return to pre-industrial CO₂ levels, the report says, a possibility that is presently beyond our wildest imaginings.

A second amplifier operates in connection with the ice sheet covering Greenland. If this melts completely it will add 7 meters to sea level rise. The surface of the ice is some 3000 metre above sea level in the interior of Greenland. Melting is already underway and as the ice melts the height of the surface is lowered and the surface

temperature therefore rises, increasing the rate of melt. This is a runaway process that leads scientists to be pessimistic about the possibility of preventing the eventual disappearance of the Greenland ice sheet.

A third polar amplifying process identified in the report is the melting of the top layers of *permafrost*. Permafrost covers large areas of the Arctic region. As it thaws it releases massive amounts of methane, which will exacerbate warming and hence accelerate the rate of methane release. This will be an unstoppable process once it gets going. The report concludes:

“Never has a single generation held the future of so many coming generations, species and ecosystems in its hands. Cryosphere climate change is not like air or water pollution, where the impacts remain local and when addressed, allow ecosystems largely to recover. Cryosphere climate change, driven by the physical laws of water’s response to the freezing point, is different. Slow to manifest itself, once triggered it inevitably forces the Earth’s climate system into a new state, one that most scientists believe has not existed for 35–50 million years.”

PERMAFROST

Let us focus on the permafrost issue. There are at least two mechanisms contributing to methane release from thawing permafrost soils. The first concerns methane generated in the so-called active layer. This is the top layer of soil that may be up to a few metres deep that thaws during the summer and refreezes during the winter. This soil is rich in organic material that rots during the summer months, giving off CO₂ and methane. Global warming deepens this active layer and accelerates the release of methane. This is a significant accelerator of global warming.

There is however a second source of methane that scientists are much more worried about. Under conditions of relatively high pressure and low temperature, methane combines with water in a crystalline structure that traps methane molecules inside a cage of water molecules. The resulting substance looks like ice and is sometimes described as methane ice. This material is often referred to as methane clathrate, clathrate for short, or methane hydrate, hydrate for short^{lxxxix}. Methane clathrates exist in very large quantities in the frozen permafrost soil. However as the soil thaws, the clathrates are not stable and break down – dissociate - into methane and water. In other words, the methane ice melts. This can be quite a rapid process, much quicker than the rate of methane production from decaying organic matter^{xc}. Scientists have discovered sink holes (craters) in the Siberian tundra that appear to have been caused

by massive bubbles of methane from melting clathrates erupting at the surface. The first of these craters, discovered in 2014, was 30 metres in diameter and well over 70 metres deep^{xci}, giving some idea of the force of the eruption and the pressure of methane that had built up below.

But something even more worrying is occurring beneath the Arctic sea. Not all permafrost is above present day sea level. The Siberian Arctic shelf is a shallow sea that was once dry land. At that time it froze to great depth, as a result of very low atmospheric temperatures. Today, under water, which is always above freezing point, it is thawing more rapidly than on land. Researchers have discovered great streams of methane venting from the seafloor and escaping into the atmosphere^{xcii}. Indeed the seascape is dotted with “hot spots” of escaping methane. There is also the possibility of a sudden and very large release of methane from the sea floor, large enough to cause a twelve fold increase in the amount of methane in the planet’s atmosphere^{xciii}. The consequences of such a release are hard to imagine. Tim Flannery warns us that among all the possible events that “might propel the world into abrupt, catastrophic and irreversible climate change, ... only one – a release of the clathrates – looms as an immediate potential threat”^{xciv}.

EXPLOITING METHANE CLATHRATES

Clathrates are found on ocean floors in many parts of the world, not just in the Arctic, and the total amount of methane locked away in this way is many times other known methane reserves. Clathrates are therefore seen by some sections of the petroleum industry as a massive resource awaiting exploitation.

To date there is one example of commercial gas production from clathrates. This is occurring from the Messoyakha field in far northern Siberia. A conventional gas reservoir was discovered in 1967 and production began in 1970. The gas pressure slowly dropped away until production ceased in 1979. But in the next three years the clathrates in the permafrost layer above the reservoir dissociated as a result of the drop in pressure, and the reservoir refilled with methane. Production began at a slower rate from 1982 and has continued since. This is the first known commercial production of methane from clathrates^{xcv}.

The possibility of producing methane from seabed hydrates in non-Arctic regions has been under study for many years and in 2013 the Japanese carried out the world’s first test production from this source^{xcvi}. Climate change activists are aghast at this development. “The Madness of Exploiting Methane Hydrates”, was the title of one article which argued that as the world moves to reduce greenhouse emissions the last

thing we need is to open up massive new reservoirs of methane. But there is another reason to be worried. The extraction of methane from seabed clathrates has the potential to cause massive underwater landslides and consequent tsunamis. The Japanese drilling and production activity has been in the Nankai trough, a known area of seismic activity, and one can only hope the Japanese authorities have thoroughly considered the risk of subsea landslide.

The risk of landslide has prompted at least one company not to pursue undersea methane hydrate deposits, even though they appear to be "easier" and cheaper to exploit^{xcvii}. Instead, the company is concentrating on permafrost regions on land. In particular it has targeted a permafrost region of the Tibetan plateau in China for its first methane hydrate production project.

A significant issue for companies seeking to exploit methane clathrates either within the permafrost or in sub-seabed locations is how to stimulate the clathrate solid to dissociate (melt), thus releasing the methane gas that will then come to the surface under its own pressure. The two most obvious ways are to reduce the pressure or to increase the temperature. The Messoyakha gas field began producing methane from clathrates because, although no one understood this at the time, draining of the gas reservoir depressurised the permafrost layer immediately above, to the point where dissociation began to occur. Other experiments since have suggested that depressurisation is indeed an effective way to stimulate dissociation^{xcviii} and can be achieved simply by drilling holes into the clathrate zone. The second method to stimulate methane production from clathrates is to increase the temperature by pumping hot water through the zone, but this is prohibitively expensive.

The reason I have gone into this detail about how companies are seeking to stimulate methane production from clathrates is not because I am advocating that course of action. It is to contrast it with the proposal I shall be making below, which presupposes that the methane is being released without any stimulation.

A ROLE FOR THE GAS INDUSTRY

So what can the gas industry do to reduce the impact of methane clathrate dissociation on climate change? To begin, if it wishes to be seen as working against climate change, it will not seek to exploit clathrates that are deep within permafrost regions and showing no sign of dissociation; it will target the streams of methane already being released, or possibly clathrates that are expected to undergo dissociation in the relatively near future.

If we focus on the hot spots in the Arctic sea that are releasing streams of methane from subsea permafrost, it may be technically possible to capture these streams before they reach the atmosphere. The industry already has the technology to place domes over subsea blowouts that enable the gas to be brought by tubing to the surface in a controlled way. One can imagine hundreds if not thousands of these structures located over the previously identified hot spots. The industry has shown itself very adept at gathering coal seam gas, as well as shale gas, from numerous widely distributed small wells, and such a scenario might be possible in the Arctic sea. If this gas was simply flared – set alight as it reached the surface – converting it to CO₂, the greenhouse effect of this Arctic release would be lessened. That in itself would be worthwhile from a climate change point of view. However if the methane gas could be collected and sold, this would produce an additional benefit.

In relation to the craters which have been discovered onshore in Siberia, Russian scientists have suggested that the eruptions that cause them might be avoided by drilling holes into the tundra to release the pressure.^{xciix} If so, the same possibilities of flaring or harvesting arise.

How can all this be in the economic interests of petroleum companies? It will depend on society finding a way to put a 'reverse' price on carbon, that is, a price that is paid to companies for harvesting methane and either converting it directly to carbon dioxide or better still, diverting it to market. There is presumably some price at which all this would become economically worthwhile. Perhaps the industry could investigate the level of carbon pricing that would make this possible, and begin to lobby for it.

6. Removing carbon from the atmosphere

The previous section described how the petroleum industry might use its expertise to counteract one of the climate change accelerators. But if we are to have any real chance of avoiding catastrophic climate change it is not enough to slow the process; we must find a way to put it into reverse. This means taking CO₂ out of the atmosphere, and ideally returning the planet's atmosphere to pre-industrial CO₂ levels. Richard Branson, the founder of Virgin Enterprises, sees this as vital for our salvation. To this end, he created the Virgin Earth Challenge in 2007. The challenge is to all comers to find a way to take one gigatonne of carbon per annum out of the atmosphere. A gigatonne is a billion tonnes, so this is indeed a challenge. The prize is commensurate. At \$25 million, it is the largest science prize ever. To date no one has won the prize but there are 11 finalists who are working towards the goal, using a variety of methods. In this section I focus on one particular method of sequestering carbon that is of particular relevance to petroleum industry - the production of char from algae.^c There are two fundamental processes involved – growing algae and then converting this to char. I deal with these processes in turn.

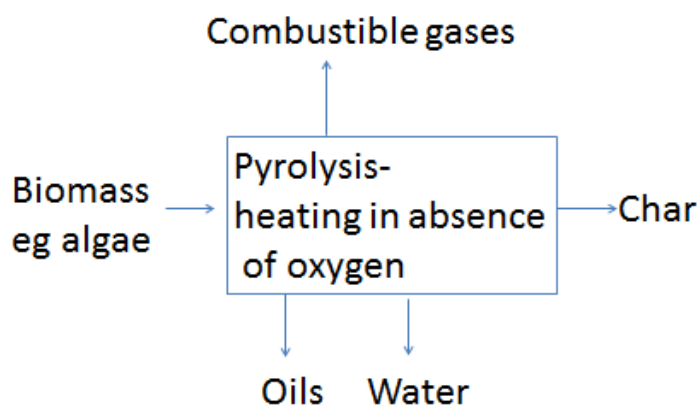
PYROLYSING ALGAE

Algae come in many forms. Seaweed is a well-known form of macro-algae and there are also many micro-algae. Given the right conditions, algae can grow with astonishing speed, as is demonstrated by the algal blooms that occur in polluted rivers and lakes. The volume of algae can double every few hours in what amounts to a chain reaction. Apart from a supply of nutrients, the basic ingredients in this chain reaction are atmospheric carbon dioxide and sunlight. Growing algae is one of the fastest ways to capture atmospheric carbon. It amounts to pumping carbon out of the atmosphere, using solar energy – a kind of solar-powered pump.

Macro algae – seaweed - can be grown on the ocean surface and seaweed farming already covers hundreds of square kilometres off the coast of China.^{ci} But algae can also be grown in closed systems called bioreactors or photo-bioreactors. For example, a tubular reactor is a system of transparent pipes through which water enriched with CO₂, nutrients and algae is pumped. New algae grow as the enriched water passes from one end of the system to the other and can be harvested as it emerges. These closed systems enable much greater control to be exercised over the process.

The second fundamental process is pyrolysis.^{cii} If you heat biomass, for example algae, in the presence of oxygen, it burns, meaning that the carbon combines with the oxygen to form CO₂. However if it is heated in the absence of oxygen, it cannot burn. What happens is that various oils and gases are driven off leaving a relatively pure form of carbon, known as char or biochar. The process is known as pyrolysis and has been practiced for thousands of years to turn wood to charcoal. Charcoal burns with particular intensity and historically was valued wherever very high temperatures were required, as in metal manufacture. The process is represented in the figure 1. The gas, when burnt, produces far more heat than is necessary to run the pyrolyser, and the excess can be used to generate electricity. The oils in the diagram are easily refined into transport fuels.

Figure 1 Pyrolysis inputs and outputs^{ciii}



Apart from burning with an intense heat, biochar has two other very important characteristics from the present point of view. First, it is a valued soil additive, and in fact is sold to agricultural users for this purpose. Second, when mixed into the soil it will survive for hundreds of years, perhaps even a thousand^{civ}. Producing char and sequestering it in soil is therefore a semi- permanent way of capturing carbon. In contrast forests are a rather less permanent way of capturing carbon since trees eventually die and rot, returning methane and carbon dioxide to the atmosphere, or alternatively burn, returning CO₂ to the atmosphere^{cv}.

Interestingly, three of the eleven Virgin Earth finalists are developing sequestration strategies based on biochar, although none of them is producing biochar from algae. That is where the petroleum industry comes in, as I shall explain in a moment.

The last thing to note about pyrolysis is that by varying the parameters of the process such as the temperature and the type of algae, one can vary the relative proportions of outputs. In particular, one can maximise char production, or alternatively, the production of oils that can be used as transport fuels. It is probably not possible to maximise both simultaneously.

THE PETROLEUM INDUSTRY

So what are petroleum companies doing about this? Interestingly, they are already heavily involved. For many years the petroleum industry has been producing biofuels, using food crops such as sugar cane, corn and soybeans which are transformed by fermentation or other chemical processes into ethanol or bio-diesel. This has been controversial, in part because of the negative consequences of the large scale monoculture farming of these crops. Petroleum companies are now funding research programs on so-called second generation biofuels, in particular on algae that can be grown on water rather than land. This will circumvent many of the criticisms of first generation biofuels^{cvi}. However, the use of biofuel eventually results in the return of carbon to the atmosphere, which will largely cancel out the carbon draw-down effect of growing algae in the first place. From the climate change point of view, it is one step forward and one step back. Nevertheless, this method of fuel production is far better than the use of fossil fuels, which involve a one way transfer of carbon to the atmosphere.

The petroleum industry is also funding research into pyrolysis. However this is not with a view to producing char, but rather, as an alternative means of processing biomass to produce biofuels. The process will inevitably produce some char which can then be sold for soil enrichment. Biofuels produced in this way might thus lead to a steady stream - perhaps only a trickle - of carbon returned to the soil. This would be a win/win for the industry and the environment.

As already noted, pyrolysis that optimises fuel production will not optimise char production. But clearly, the petroleum industry is well placed to take the lead in developing a process that optimises char production, in addition to one that optimises biofuel production. For char production to be an economic proposition, markets will need to be developed, and the industry will no doubt need to be paid a monetary price for carbon sequestered in this way. It is not hard to envisage this becoming a further win/win for the industry and the environment.

The fossil fuel industry is anxiously awaiting developments with carbon capture and storage that will enable it to capture its emissions and store them safely underground

for millennia. However there is an alternative. Rather than capturing its own emissions, the same effect can be achieved by taking an equivalent amount of carbon out of the atmosphere by other means. The pyrolysis of algae, on a large enough scale would achieve just this. A system of carbon credits would then enable the industry to claim carbon neutrality. The oil and gas industry therefore has an enormous interest in developing technologies to remove carbon from the atmosphere, if it is to survive in the long term.

7. Carbon capture and storage

Finally, a few words about carbon capture and storage (CCS). By this I mean the capture and storage of carbon *dioxide*; section 6 of this paper was about the capture and storage of relatively pure carbon - char. As noted earlier, CCS is the last hope for the coal industry. If the carbon dioxide produced by burning coal can be effectively captured and securely stored underground, this will provide a new lease of life for the coal industry. For this reason CCS is a two edged sword for the petroleum industry. If the problem of CCS is effectively solved, the competitive advantage that gas has from an environmental point of view will be wiped out. In the context of this paper, this is indeed a significant issue.

STORAGE

It is convenient to deal separately with the two processes of capture and storage - storage first. There are various underground storage possibilities. One is the use of depleted oil and gas reservoirs. Another is the use of previously unpenetrated layers, deep underground, which are naturally porous enough to absorb CO₂ pumped down into them^{cvii}. There are others. The petroleum industry, and in particular its geologists, have much to contribute in identifying suitable, secure underground storage sites. Once these sites are identified, the industry is well positioned to drill the necessary wells and pump CO₂ under high pressure into storage.

Questions remain however about how long lasting this form of storage may be. Will it be secure for hundreds, even thousands of years? Who will be responsible in the long term for the security of storage, especially when ownership may change hands several times?^{cviii} The proponents of CCS have tended not to focus on these questions. In Australia, the CSIRO had this to say about the security of storage, in a question and answer pamphlet it produced.

Leaks from surface facilities, such as wells and pipelines, would be readily detectable, and could be dealt with by the types of procedures that the petroleum industry already uses for oil and gas facilities. In the unlikely event that CO₂ was to permeate to the surface, a gradual escape of CO₂ would be expected and would be dissipated by the wind, as normally occurs when CO₂ is vented naturally in volcanically active areas^{cix}.

This statement is questionable for two reasons. First, it is unjustifiably optimistic about the industry's capacity to guarantee security of storage. The Aliso Canyon blowout

described earlier shows just what can happen. Importantly, that blowout was caused not by unpredicted geological conditions but by the failure of a well which had been drilled into the storage area. As these wells age, such catastrophic failures become more likely.

Secondly, the comment about wind dispersal suggests that the writers have lost sight of the main issue. From a climate point of view it is not the local concentration of escaping CO₂ that is relevant, but the contribution of the seepage to overall CO₂ levels. Of course if any one storage system begins to leak in this way it may not have a discernible effect on atmospheric CO₂ levels, but if over time many of these storage facilities fail, the whole strategy of CCS is undermined.

CAPTURE

Consider now what is perhaps the harder issue - carbon capture. Although CCS has been discussed for decades the problem of capturing emissions from fossil fuel electricity generators has not yet been solved. There are some examples of CCS operating successfully, but the prospect of emission-free fossil-fuel power generation seems a long way off. Research continues, however. For example it has become apparent that CO₂ can be effectively captured by passing fossil fuel exhaust gas through *fuel cells*.^{cx}

One particular technology is worth singling out for mention, in part because of the high level of US government support it has received. This is the gasification of coal, which produces synthetic gas for subsequent use in gas-fired generators, in addition to large quantities of CO₂ which must be sequestered. The US government has championed this technology by subsidising the construction of a commercial plant in Mississippi. However the project has been beset by mismanagement and massive cost over-runs and has proved a financial disaster^{cxii}. Although this may not constitute a fair test of the technology, it has led to a higher level of scepticism about whether we will see commercially viable carbon capture from coal-fired power stations in the near future.

It needs to be stressed that even had this project delivered on expectations it would not have captured all emissions. Proponents claimed only that it would be no more polluting than a modern gas fired power station^{cxiii}. Even accepting their claim at face value, this is not the way to a zero emissions future.

Finally, even if the issues of capture are resolved, the question remains of how to finance the construction of pipelines to transport the captured CO₂ to storage sites that may be long distances away.

In Australia one of the celebrated examples of CCS is Chevron's project on Barrow Island, off the coast of WA. This needs to be put in perspective. Chevron is producing gas offshore and piping it onto the island for processing. The raw gas contains on average 14% CO₂^{cxiii} which needs to be removed before the remaining methane can be liquefied for transportation. Separating out the CO₂ is thus commercially necessary, quite independently of any environmental benefits. But rather than venting this gas into the atmosphere, Chevron has found a suitable depository - the Dupuy formation - more than two kilometres below the surface of Barrow Island, where CO₂ can be sequestered. There is thus no issue of long distance transportation to storage. Chevron's technology involves separating CO₂ from sales gas, not the capture of the carbon dioxide produced when the sales gas is finally burnt by customers. So while this is an important advance, it has no direct implications for the capture of emissions from fossil fuel fired power stations. What it will do is to help Chevron keep production costs down when carbon emissions are eventually priced^{cxiv}.

THE ULTIMATE ISSUE

I have reserved the most important point till last. No matter how effective carbon capture and storage is, it can only be part of the solution to climate change. In theory it might give us zero emissions electricity, just as renewables currently do. But that is not enough to stop the runaway climate change that climate scientists believe may now be occurring. We must do more. We must start to remove carbon from the atmosphere and we must try to break the vicious cycle of methane release from melting permafrost. Neither CCS nor renewables have the potential to do this.

8. Conclusion

This paper has argued that placing a price on carbon emissions will benefit the gas industry at the expense of coal and is therefore something which the industry should lobby for. To make its argument more persuasive it must do its utmost to eliminate fugitive emissions and to prevent large scale reservoir blowouts.

The paper also argued that the way the industry can make the greatest contribution to combatting climate change is to look beyond zero human emissions to reducing nature's methane emissions such as are occurring in the Arctic, as well as to ways of drawing down carbon dioxide from the atmosphere by techniques such as the pyrolysis of fast growing algae to produce char.

These latter activities depend on a different kind of price on carbon, a price that society pays to companies for removing carbon from the atmosphere. It will not be profitable for the petroleum industry to become a climate saviour in this way unless the price is right. The industry therefore needs to take the lead in lobbying for a price that will make these developments possible. But where will the money come from? The Paris agreement of December 2015 stipulated that the advanced nations of the world should find \$100 billion per year to facilitate sustainable the development of the poorer nations on earth. If the advanced nations could find a similar amount to pay the petroleum industry and others to reduce nature's emissions and to draw down atmospheric carbon, this might well give us real cause for hope. Just as importantly, it would transform the petroleum industry from a climate pariah, as some see it, to a climate saviour.

Finally, this paper is really work in progress. The next step is to examine more closely what the petroleum industry can do to remove carbon from the atmosphere and to capture arctic methane emissions, and perhaps to identify other win/win options. I would welcome input from the industry on these matters.

Recommendations

TO THE PETROLEUM INDUSTRY

The industry should lobby for a price on carbon that will help it to take market share from coal more quickly.

The industry should minimize methane leakage from all stages of the gas supply chain.

The industry should identify the financial incentives that would make it worthwhile capturing methane leakage from the permafrost.

The industry should explore ways of converting atmospheric carbon dioxide to biochar for long term storage and identify the financial incentives that would make this worthwhile.

TO GOVERNMENTS

Governments should cooperate with the petroleum industry to develop financial incentives to capture Arctic methane releases and to create and sequester biochar.

About the Author

Andrew Hopkins is Emeritus Professor of Sociology at the Australian National University in Canberra. He has written widely on the prevention of major accidents in hazardous industries, particularly in the petroleum industry. Among his books are:

[*Lessons from Longford: The Esso Gas Plant Explosion*](#) (CCH, Sydney, 2000)

[*Failure to Learn: The BP Texas City Refinery Disaster*](#) (CCH, Sydney, 2008)

[*Disastrous Decisions: The Human and Organisational Causes of the Gulf of Mexico Blowout*](#) (CCH: Sydney, 2012)

For a semi- autobiographical statement see his

[*Quiet Outrage: The Way of a Sociologist*](#) (CCH, Sydney, 2015)

Contact: Andrew.hopkins@anu.edu.au

Endnotes

-
- ⁱ This paper takes it for granted that the planet is experiencing human-induced climate change.
- ⁱⁱ This is predicted in a recent paper by Paul Stevens (May 2016) *International Oil Companies The Death of the Old Business Model*, The Royal Institute of International Affairs, Chatham House: <https://www.chathamhouse.org/sites/files/chathamhouse/publications/research/2016-05-05-international-oil-companies-stevens.pdf>
- ⁱⁱⁱ E Lowe and R Harris (1998) *Taking Climate Change Seriously: British Petroleum's Business Strategy*: <http://www.sciencedirect.com/science/article/pii/S1066793800800639>
- ^{iv} Tom Bergin (2011) *Spills and Spin: The Inside Story of BP*, Random House, London, p59
- ^v Tom Bergin and Sarah Young (21 December 2011) "BP Turns Out the Lights Bergen and others", *Reuters*: <http://www.reuters.com/article/us-bp-solar-idUSTRE7BK1CC20111221>
- ^{vi} Tom Bergin (2011) *Spills and Spin: The Inside Story of BP*, Random House, London, pp59-60
- ^{vii} Bergin, p52
- ^{viii} Terry Macalister (15 May 2016) "Shell creates green energy division to invest in wind power", *The Guardian*: <https://www.theguardian.com/business/2016/may/15/shell-creates-green-energy-division-to-invest-in-wind-power>
- ^{ix} Ibid
- ^x "Ports and Transport" (n.d.) Minerals Council of Australia: http://www.minerals.org.au/resources/coal/exports/ports_and_transport
- ^{xi} "Six oil majors say: We will act faster with stronger carbon pricing" (1 June 2015) Open Letter to UN and governments: <http://newsroom.unfccc.int/unfccc-newsroom/major-oil-companies-letter-to-un/>
- ^{xii} Shell (2014) Shell Annual Report and Form 20F, P6: <http://www.shell.com/media/annual-reports-and-publications.html>
- ^{xiii} Joe Carroll and Bradley Olson (28 May 2015) "Exxon, Chevron Say No Thanks to European Peers on Climate", *Bloomberg*: <http://www.bloomberg.com/news/articles/2015-05-27/exxon-ceo-says-it-won-t-give-lip-service-on-climate>
- ^{xiv} *Oil & Gas UK Statement on COP21 Agreement* (14 December 2015) Oil & Gas UK: <http://oilandgasuk.co.uk/oil-gas-uk-statement-on-cop21-agreement/>
- ^{xv} *Climate Change and Energy* (November 2015) API: <http://www.api.org/~media/Files/Policy/Environment/Climate-Change-and-Energy/CLIMATE-PRIMER.pdf?la=en>
- ^{xvi} *Climate change policy principles*, 2nd ed. (December 2015) Australian Petroleum Production & Exploration Association: <http://www.appea.com.au/wp-content/uploads/2016/02/Climate-Change-Policy-Principles-APPEA-final.pdf>
- ^{xvii} *Repeal of the Carbon Tax – How the Carbon Tax Works* (n.d.) Australian Department of the Environment: http://www.environment.gov.au/system/files/pages/59388d77-a9b5-4e4c-87b7-d732baf7c45b/files/factsheet-how-carbon-tax-works_1.pdf
- ^{xviii} APPEA's policy is that trade exposed industries should be exempt from a carbon price. That would include export coal producers.
- ^{xix} Rebekah Kebede (11 June 2011) "Q+A-Australia's carbon tax and the LNG industry", *Reuters*: <http://www.reuters.com/article/carbon-tax-lng-idUSL3E7IB1CY20110711>
- ^{xx} Australian Petroleum Production & Exploration Association (13 April 2011) *2011 APPEA Conference & Exhibition Daily Newspaper*: http://resolutions-group.com.au/images/the_daily_review/APPEA%20Daily%20Review%20day%203.pdf
- ^{xxi} Dennis Shanahan (11 April 2011) "Gas giants seek carbon tax breaks", *The Australian*: <http://www.theaustralian.com.au/national-affairs/climate/gas-giants-seek-carbon-tax-breaks/story-e6frg6xf-1226036923679>

-
- ^{xxii} Poten & Partners (31 July 2011) “Carbon Tax Unlikely To Derail Australia’s LNG Industry” *Monthly LNG Opinion*: http://www.poten.com/wp-content/uploads/2015/05/LNG_Opinion_20110801.pdf
- ^{xxiii} Australian Petroleum Production & Exploration Association (17 July 2014) “Carbon tax repeal removes cost burden on LNG exporters”: http://www.appea.com.au/media_release/carbon-tax-repeal-removes-cost-burden-on-lng-exporters/
- ^{xxiv} See for example the websites of American Coal Council (<http://www.americancoalcouncil.org>) and the Australian coal industry auspiced by the Australian Minerals Council (<http://www.minerals.org.au>).
- ^{xxv} Andrew Duffy (27 September 2011) “Coal industry slams carbon tax”, *Australian Mining*: <http://www.australianmining.com.au/News/Coal-industry-slams-carbon-tax>
- ^{xxvi} Cole Latimer (17 July 2014) “Carbon tax repealed”, *Australian Mining*: <http://www.australianmining.com.au/news/carbon-tax-repealed>
- ^{xxvii} International Council on Mining & Metals (21 October 2015) “ICMM issues statement on climate change”: <https://www.icmm.com/news-and-events/news/icmm-issues-statement-on-climate-change>
- ^{xxviii} Anglo American (n.d.) *Anglo American Position Statement: Climate Change*: <http://www.angloamerican.com/~media/Files/A/Anglo-American-PLC-V2/documents/approach-and-policies/environment/climate-change-position-statement-september-2015.pdf>
- ^{xxix} Anglo American (2014) *Sustainable Development Report*, p69: <http://www.angloamerican.com/~media/Files/A/Anglo-American-PLC-V2/report-builder-2014/sdr/sdr14-interactive-version.pdf>
- ^{xxx} Anglo American (16 February 2016) “Anglo American Announced Wide-Ranging Portfolio Changes”: <http://australia.angloamerican.com/media/press-releases/pr-2016/160216>
- ^{xxxi} Centennial Coal (2014) *Year in Review*, p16: <http://rescuehne.realviewdigital.com/?iid=127523#folio=18>
- ^{xxxii} BHP Billiton (n.d.) *Climate Change: Portfolio Analysis*, p7: <http://www.bhpbilliton.com/~media/5874999cef0a41a59403d13e3f8de4ee.ashx>
- ^{xxxiii} Scott Gossard (18 June 2015) *Power Engineering*: <http://www.power-eng.com/articles/print/volume-119/issue-6/features/coal-to-gas-plant-conversions-in-the-u-s.html>; Christina Nunez (20 November 2014) “A Slew of Coal Plants Get New Lease on Life—With Gas”, *National Geographic*: <http://news.nationalgeographic.com/news/energy/2014/11/141120-coal-plants-repowered-with-natural-gas/>
- ^{xxxiv} See for example the film *Under the Dome*
- ^{xxxv} Kathy Chen and David Stanway (22 May 2015) “Beijing promises coal-free power by 2017 to fight pollution”, *Reuters*: <http://www.reuters.com/article/us-china-pollution-beijing-idUSKBN0070V920150522>
- ^{xxxvi} In particular combined cycle power stations.
- ^{xxxvii} Rachel Cleetus (7 August 2015) “Four Ways the Final Clean Power Plan Limits the Rush to Natural Gas”, *Union of Concerned Scientists*: <http://blog.ucsusa.org/rachel-cleetus/four-ways-the-final-clean-power-plan-limits-the-rush-to-natural-gas-839>
- ^{xxxviii} Pfiefer et al (2016) have recently calculated that if we wish to restrict global warming to 2 degrees, as envisaged by the 2015 Paris agreement, we will have to stop building new fossil fuel power stations in 2017. This is a startling finding. By 2017 the existing world-wide stock of fossil fuel power stations, if operated to the end of their normal lives, will have driven CO₂ levels to the point where any further rise will make it impossible to limit global warming to 2 degrees. (“The ‘2⁰C capital stock’ for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy”,. However new gas fired power stations could still be built to *replace* existing coal-fired stations, without exceeding the limit, although they might not be able to continue to the end of *their* normal operating lives.
- ^{xxxix} “Converting an existing boiler is typically 15% to 30% of the cost of installing a new natural gas boiler”. John Ingraham, Jim Marshall and Randy Flanagan (3 January 2014) *POWER Magazine*: <http://www.powermag.com/practical-considerations-for-converting-industrial-coal-boilers-to-natural-gas/>; see also Scott Goddard (18 June 2015) “Coal-To-Gas Plant Conversions in the U.S”, *Power Engineering*: <http://www.power-eng.com/articles/print/volume-119/issue-6/features/coal-to-gas-plant-conversions-in-the-u-s.html>

-
- ^{xi} Brian Reinhart, Alap Shah, Mark Dittus, Una Nowling and Bob Slettehaugh (12 December 2012) *Paper of the Year: A Case Study on Coal to Natural Gas Fuel Switch*, Black & Veatch: <http://bv.com/Home/news/solutions/energy/paper-of-the-year-a-case-study-on-coal-to-natural-gas-fuel-switch>
- ^{xii} Jeff Deyette (7 August 2015) "EPA Expands the Role of Renewable Energy in the Final Clean Power Plan", Union of Concerned Scientists: <http://blog.ucsusa.org/jeff-deyette/role-of-renewable-energy-final-clean-power-plan-838>
- ^{xiii} Rachel Cleetus (7 August 2015) "Four Ways the Final Clean Power Plan Limits the Rush to Natural Gas", Union of Concerned Scientists: <http://blog.ucsusa.org/rachel-cleetus/four-ways-the-final-clean-power-plan-limits-the-rush-to-natural-gas-839>
- ^{xiii} It has been argued the clean power plan was designed in a process that implicitly puts a price on carbon and that a policy of directly pricing carbon rather than imposing a complex administrative rule would have been simple. Michael Warra (10 June 2014) "What's In the BSER: EPA's Process for Setting State Goals in the Clean Power Plan", Resources for the Future: <http://www.rff.org/blog/2014/what-s-bser-epa-s-process-setting-state-goals-clean-power-plan>
- ^{xiv} James Chessell (4 June 2015) "Woodside CEO slams coal industry: 'Give me a break, who coined clean coal'", *Australian Financial Review*: <http://www.afr.com/business/mining/coal/woodside-ceo-slams-coal-industry-give-me-a-break-who-coined-clean-coal-20150603-ghg72x>
- ^{xiv} Angela Macdonald-Smith (8 June 2015) "Woodside Petroleum CEO Peter Coleman's attack on coal leaves politicians fuming", *Sydney Morning Herald*: <http://www.smh.com.au/business/woodside-petroleum-ceo-peter-colemans-attack-on-coal-leaves-politicians-fuming-20150607-ghiqst.html>
- ^{xvi} Angela Macdonald-Smith (8 June 2015) "Woodside Petroleum CEO Peter Coleman's attack on coal leaves politicians fuming", *Sydney Morning Herald*: <http://www.smh.com.au/business/woodside-petroleum-ceo-peter-colemans-attack-on-coal-leaves-politicians-fuming-20150607-ghiqst.html>
- ^{xvii} Information in this paragraph comes from Angela Macdonald-Smith (8 June 2015) "Woodside Petroleum CEO Peter Coleman's attack on coal leaves politicians fuming", *Sydney Morning Herald*: <http://www.smh.com.au/business/woodside-petroleum-ceo-peter-colemans-attack-on-coal-leaves-politicians-fuming-20150607-ghiqst.html>
- ^{xviii} Origin Energy (14 Dec 2015) "Origin welcomes Paris climate agreement": <https://www.originenergy.com.au/content/dam/origin/about/investors-media/docs/origin-welcomes-paris-climate-agreement-151214.pdf>
- ^{xix} Australian Conservation Foundation (1 March 2016) *Australia's 10 biggest climate polluters*, p9: https://d3n8a8pro7vhmx.cloudfront.net/auscon/pages/716/attachments/original/1465199065/29.02.16_ACF_Big_Polluter's_Report_2016_final.pdf
- ⁱ "There is currently a significant funding gap (>40%) preventing a baseload Power Tower CSP plant from being an attractive, private sector investment in Port Augusta". Alinta Energy (23 April 2015) *Port Augusta Solar Thermal Generation Feasibility Study*, slide 48: https://alintaenergy.com.au/Alinta/media/Documents/Alinta_Solar_Thermal_Stakeholder_Briefing_23_April.pdf. See also, Giles Parkinson (23 September 2015) "Alinta walks away from solar tower proposal for Port Augusta", *Renew Economy*: <http://reneweconomy.com.au/2015/alinta-walks-away-from-solar-tower-proposal-for-port-augusta-33892>. At the time of writing the government has announced that it will fund a solar thermal power station at Port August if it wins office in the forthcoming election. Peter Jean (18 May 2016) "Liberals promise to help fund construction of Port Augusta solar thermal power station", *Adelaide Advertiser*: <http://www.adelaidenow.com.au/news/south-australia/liberals-promise-to-help-fund-construction-of-port-augusta-solar-thermal-power-station/news-story/9fde53f07cdee969d339c69022d88ab0>
- ⁱⁱ See Anthony Ingraffea in Bobby Magill (13 February 2014) "Natural Gas May Benefit Climate Despite Methane Leaks", *Climate Central*: <http://www.climatecentral.org/news/burning-natural-gas-benefits-climate-despite-methane-leaks-17061>
- ⁱⁱⁱ Fiona Harvey, "'Golden age of gas' threatens renewable energy, IEA warns", *The Guardian*: <https://www.theguardian.com/environment/2012/may/29/gas-boom-renewables-agency-warns>

-
- ^{liii} Damian Barrett and Stuart Day (1 August 2014) “Coal seam gas emissions lower than US: first Australian study”, *The Conversation*: <https://theconversation.com/coal-seam-gas-emissions-lower-than-us-first-australian-study-29699>
- ^{liv} Darren Osborne interviewing Damian Barrett (4 December 2013) “What is fracking?”, *ABC Science*: <http://www.abc.net.au/science/articles/2013/12/04/3861669.htm>
- ^{lv} Dennis Cooke (16 August 2011) “Explainer: coal seam gas, shale gas and fracking in Australia”, *The Conversation*: <https://theconversation.com/explainer-coal-seam-gas-shale-gas-and-fracking-in-australia-2585>
- ^{lvi} Barry Stevens (22 April 2015) “It’s Not Fracking to be Concerned with, It’s a Fugitive Hiding Along the Supply Chain that is A Clear-and- Present Danger!”, *BarryOnEnergy*: <https://barryonenergy.wordpress.com/2015/04/22/its-not-fracking-to-be-concerned-with-its-a-fugitive-hiding-along-the-supply-chain-that-is-a-clear-and-present-danger/>
- ^{lvii} See previous note.
- ^{lviii} Mat Hope (3 July 2014) “Explained: Fugitive methane emissions from natural gas production”, *Carbon Brief*: <http://www.carbonbrief.org/explained-fugitive-methane-emissions-from-natural-gas-production>
- ^{lix} The Center for Media and Democracy (n.d.) “Natural gas transmission leakage rates”, *Sourcewatch*: http://www.sourcewatch.org/index.php/Natural_gas_transmission_leakage_rates
- ^{lx} Hendrick M et al, “Fugitive emissions from leak-prone natural gas distribution in urban environments”, *Environmental Pollution*, 213 (2016): 710-716, p711: <http://www.ncbi.nlm.nih.gov/pubmed/27023280>
- ^{lxi} Chris Harvey (June 2013) *Energy Efficiency Opportunities in Gas Transmission Pipelines and Distribution Networks*, Australian Department of Resources, Energy and Tourism: <http://ris.dpmc.gov.au/files/2013/07/EEO-to-energy-networks-attachment-2-RIS.doc>
- ^{lxii} Hendrick, op cit
- ^{lxiii} , Hendrick, op cit, p17. Also *Inside Climate News* 7 Dec 2015, and 8 April 2016
- ^{lxiv} Lisa Song (28 January 2015) “Methane Leaks From Gas Pipelines Far Exceed Official Estimates, Harvard Study Finds”, *Inside Climate News*: <http://insideclimatenews.org/news/20150128/methane-leaks-gas-pipelines-far-exceed-official-estimates-harvard-study-finds>
- ^{lxv} Ethan Warner et al (August 2015) *Potential Cost-Effective Opportunities for Methane Emission Abatement*, Joint Institute for Strategic Energy Analysis: <http://www.nrel.gov/docs/fy16osti/62818.pdf>
- ^{lxvi} *Inside Climate News (ICN) 22 Jan 2016*.
- ^{lxvii} Core Energy Group (February 2015) *Gas Storage Facilities: Eastern and South Eastern Australia*, Australian Energy Market Operator: http://www.aemo.com.au/Gas/Planning/Gas-Statement-of-Opportunities/~/_media/Files/Gas/Planning/Reports/GSOO/2015/Core%20%20Gas%20Storage%20Facilities.ashx
- ^{lxviii} Brenda Gazzar (3 January 2016) “Attorneys: SoCalGas could have prevented Porter Ranch gas leak with right safety measures”, *Los Angeles Daily News*: <http://www.dailynews.com/environment-and-nature/20160103/attorneys-socalgas-could-have-prevented-porter-ranch-gas-leak-with-right-safety-measures>
- ^{lxix} Tyler Durden (25 December 2015) “‘Unstoppable’ California Gas Leak Now Being Called Worst Catastrophe Since BP Spill”, *Zero Hedge*: <http://www.zerohedge.com/news/2015-12-24/unstoppable-california-gas-leak-now-being-called-worst-catastrophe-bp-spill>
- ^{lxx} Phil McKenna (7 January 2016) “California Declares State of Emergency as Leak Becomes Methane Equivalent of Deepwater Horizon”, *Inside Climate News*: <https://insideclimatenews.org/news/07012016/emergency-declared-california-massive-methane-leak-aliso-canyon-so-cal-evacuations-health-benzene-climate-change>
- ^{lxxi} McKenna (2016), *Leaking Well Temporarily Plugged as New Questions Arise About SoCal Gas’ Actions*, <https://insideclimatenews.org/news/12022016/leaking-well-temporarily-plugged-socal-gas-aliso-canyon-porter-ranch>
- ^{lxxii} McKenna (2016) *What Will Be the Health Impact of 100+ Days of Exposure to California’s Methane Leak?*, <https://insideclimatenews.org/news/17022016/health-impacts-aliso-canyon-porter-ranch-methane-leak-california-socal-gas>
- ^{lxxiii} ditto

-
- ^{lxxiv} Justin Worland (14 January 2016) "This Is How Much the California Gas Leak Is Hurting the Planet", *Time Magazine*: <http://time.com/4180692/california-methane-gas-leak-environment/?xid=homepage>
- ^{lxxv} McKenna (25 February 2016) *Aliso Canyon Released 97,000 Tons of Methane, Biggest U.S. Leak Ever, Study Says*, <https://insideclimatenews.org/news/25022016/socal-gas-hedges-measuring-its-methane-leak-new-study-gives-it-big-number>
- ^{lxxvi} Lovett and Wines (4 March 2016) *California Gas Leak Threatens Jerry Brown's Image as a Climate Change Hero*, http://www.nytimes.com/2016/03/05/us/california-gas-leak-threatens-jerry-browns-image-as-a-climate-change-hero.html?_r=2
- ^{lxxvii} Phil McKenna (11 January 2016) "Company Behind Methane Leak Is Ordered to Offset the Climate Damage", *Inside Climate News*: <https://insideclimatenews.org/news/10012016/california-methane-leak-so-cal-gas-company-ordered-offset-carbon-emissions-climate-change-governor-brown>
- ^{lxxviii} See Andrew Hopkins (2012) *Disastrous Decisions: The Human and Organisational Causes of the Gulf of Mexico Blowout*, CCH, Sydney: <http://www.cchbooks.com.au/disastrous-decisions-the-human-and-organisational-causes-of-the-gulf-of-mexico-blowout/>
- ^{lxxix} Enerknol Research (25 January 2016) *California Leak Exposes Risks Of Increasing Reliance On Natural Gas*: <https://enerknol.com/wp-content/uploads/2016/01/EKR-FF-California-Natural-Gas-Leak-Risks-1-25-2016.pdf>
- ^{lxxx} Wikipedia (n.d.) "Aliso Canyon gas leak": https://en.wikipedia.org/wiki/Aliso_Canyon_gas_leak
- ^{lxxxii} See further Ingrid Lobet (21 January 2016) "California Examines Safety Of Gas Wells Amid Methane Leak", *All Things Considered*, National Public Radio: <http://www.npr.org/2016/01/21/463865377/californiaexaminessafetyofgaswellsamidmethaneleak>
- ^{lxxxiii} Phil McKenna (8 February 2016) "New federal gas storage regulations likely to mimic industry's guidelines", *Inside Climate News*: <http://insideclimatenews.org/news/08022016/federal-gas-storage-regulations-likely-mimic-industry-guidelines-aliso-canyon-phmsa-api>
- ^{lxxxiv} See Andrew Hopkins (2008) *Failure to Learn: The BP Texas City Refinery Disaster*, CCH, Sydney: <http://www.cchbooks.com.au/failure-to-learn-the-bp-texas-city-refinery-disaster/> and Andrew Hopkins (2012) *Disastrous Decisions: The Human and Organisational Causes of the Gulf of Mexico Blowout*, CCH, Sydney: <http://www.cchbooks.com.au/disastrous-decisions-the-human-and-organisational-causes-of-the-gulf-of-mexico-blowout/>
- ^{lxxxv} See Andrew Hopkins (2000) *Lessons from Longford: The Esso Gas Plant Explosion*, CCH, Sydney: <http://www.cchbooks.com.au/lessons-from-longford-the-esso-gas-plant-explosion/>
- ^{lxxxvi} Tim Walker (2 January 2016) "California methane gas leak 'more damaging than Deepwater Horizon disaster'", *The Independent*: <http://www.independent.co.uk/news/world/americas/california-methane-gas-leak-more-damaging-than-deepwater-horizon-disaster-a6794251.html>
- ^{lxxxvii} Jan Hayes & Andrew Hopkins (2014) *Nightmare Pipeline Failures*, CCH, Sydney, chapter 10: <http://www.cchbooks.com.au/nightmare-pipeline-failures-fantasy-planning-black-swans-and-integrity-management/>
- ^{lxxxviii} International Cryosphere Climate Initiative (December 2015) *Thresholds and Closing Windows*: http://iccinet.org/wp-content/uploads/2015/11/ICCI_thresholds_v6b_151203_high_res.pdf
- ^{lxxxix} *Thresholds and Closing Windows*, chapter 3
- ^{xc} A clathrate is a chemical substance consisting of a lattice that traps or contains other molecules. The most famous clathrates are methane clathrates where the hydrogen-bonded framework is contributed by water and the guest molecules are methane. Because the lattice in this case is made of water molecules, the substance is also called methane hydrate.
- ^{xc} University of Alaska Fairbanks (5 March 2010) "Methane releases from Arctic shelf may be much larger and faster than anticipated", *Science Daily*: <https://www.sciencedaily.com/releases/2010/03/100304142240.htm>
- ^{xcii} Katia Moskvitch (31 July 2014) "Mysterious Siberian crater attributed to methane", *Nature*: <http://www.nature.com/news/mysterious-siberian-crater-attributed-to-methane-1.15649>
- ^{xciii} Steve Connor (13 December 2011) "Vast methane 'plumes' seen in Arctic Ocean as sea ice retreats", *The Independent*: <http://www.independent.co.uk/news/science/vast-methane-plumes-seen-in-arctic-ocean-as-sea-ice-retreats-6276278.html>

-
- ^{xciii} See Wikipedia (n.d.) “Arctic methane emissions”:
https://en.wikipedia.org/wiki/Arctic_methane_emissions
- ^{xciv} Tim Flannery (2015) *Atmosphere of Hope*, Text Publishing, pp57, 65:
<https://www.textpublishing.com.au/books/atmosphere-of-hope>
- ^{xcv} Yuri F. Makogon et al (2 July 2005) “Russian field illustrates gas hydrate production”, *Oil and Gas Journal*: <http://www.ogj.com/articles/print/volume-103/issue-5/drilling-production/russian-field-illustrates-gas-hydrate-production.html>
- ^{xcvi} Andy Rowell (13 March 2013) “The Madness of Exploiting Methane Hydrates”, Oil Change International: <http://priceofoil.org/2013/03/13/the-madness-of-exploiting-methane-hydrates/>
- ^{xcvii} Tundra Gas Inc (n.d.) “Methane Hydrate”: <http://www.tundragas.com/methane-hydrate.html> and Tundra Gas Inc (n.d.) “What We Do and How We Do It”: <http://www.tundragas.com/business-outline.html>
- ^{xcviii} *ibid*
- ^{xcix} Katia Moskvitch (31 July 2014) “Mysterious Siberian crater attributed to methane”, *Nature*:
<http://www.nature.com/news/mysterious-siberian-crater-attributed-to-methane-1.15649>
- ^c Richard Sayre (2010) “Microalgae: The Potential for Carbon Capture”, *BioScience*:
<http://bioscience.oxfordjournals.org/content/60/9/722.full> and “Arctic Methane Monster Shortens Tail: Shakova, Semiletov Study Shows ESAS Emitting Methane at Twice Expected Rate” (12 December 2013) *robertscribblers*: <https://robertscribblers.com/2013/12/12/arctic-methane-monster-shortens-tail-shakova-semiletov-study-shows-esas-emitting-methane-at-twice-expected-rate/>. See also see Tim Flannery (2015) *Atmosphere of Hope*, chapter 16.
- ^{ci} Flannery op cit, p166
- ^{cii} “Pyrolysis” (n.d.) Bioenergy Wiki: <http://www.bioenergywiki.net/pyrolysis>
- ^{ciii} Crucible Carbon (n.d.) “Pyrolysis”:
<http://www.anzbiochar.org/images/logos/Crucible%20Carbon%20One%20Page%20Flyer.pdf>
- ^{civ} The Climate Institute (March 2014) *Below Zero*:
http://www.climateinstitute.org.au/verve/resources/BelowZero_March2014.pdf
- ^{cv} International Biochar Institute (n.d.) “Frequently Asked Questions About Biochar: What is Biochar?”:
<http://www.biochar-international.org/biochar/faqs#question1>
- ^{cvi} ExxonMobil (n.d.) “Advanced biofuels”: <http://corporate.exxonmobil.com.au/en-au/energy/research-and-development/advanced-biofuels/energy-investments-advanced-biofuels>
- ^{cvi} An example of this type of storage is Chevron’s celebrated CCS project on Barrow Island off the coast of WA.
- ^{cvi} David Bookbinder (7 July 2016) “Lack of Regulation Is as Big a Problem as Costs for Carbon Capture”, *New York Times*: <http://www.nytimes.com/roomfordebate/2016/07/07/clean-coal-or-a-dirty-shame/lack-of-regulation-is-as-big-a-problem-as-costs-for-carbon-capture>
- ^{cix} CSIRO (n.d.) *Carbon Capture and Storage – Frequently Asked Questions*: <http://ngl.org.au/wp-content/uploads/2014/08/Carbon-Capture-and-Storage-Frequently-Asked-Questions.pdf>
- ^{cx} John Schwartz (5 May 2016) “Exxon Mobil Backs Fuel Cell Effort to Advance Carbon Capture Technology”, *New York Times*: http://www.nytimes.com/2016/05/06/science/exxon-mobil-backs-fuelcell-effort-to-advance-carbon-capture-technology.html?_r=0
- ^{cx} Ian Urbina (5 July 2016) “Piles of Dirty Secrets Behind a Model ‘Clean Coal’ Project”, *New York Times*:
<http://www.nytimes.com/2016/07/05/science/kemper-coal-mississippi.html>
- ^{cxii} Wikipedia (n.d.) “Kemper Project”: https://en.wikipedia.org/wiki/Kemper_Project and Mississippi Power (n.d.) *Gasification and TRIG*: <http://www.mississippipower.com/about-energy/plants/kemper-county-energy-facility/gasification-and-trig>
- ^{cxiii} Chevron Australia (n.d.) *Carbon Dioxide Injection: WorldClass Technology*:
<https://www.chevronaustralia.com/our-businesses/gorgon/carbon-dioxide-injection>
- ^{cxiv} The project will reduce carbon dioxide emissions from the production process by 40%. Chevron Australia (n.d.) *Carbon Dioxide Injection Project*: <https://www.chevronaustralia.com/docs/default-source/default-document-library/fact-sheet-gorgon-co2-injection-project.pdf?sfvrsn=8>