Whether we personally choose to concern ourselves about the future or not, humans, and for that matter, most living beings on earth are facing one of the greatest challenges we have ever witnessed. The climate is changing, and for the worst for most of us. To stop this we have to wean ourselves off fossil fuels, and fast. Choosing the right mix of alternative energy sources from the outset is of vital importance. This book provides an overview of the climate challenge and explores the various energy sources and savers available to us, examining the pros and cons of each as to their likely effectiveness in this great challenge. There is much to be hopeful about but urgency is paramount.
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Preface

Some of us may be forgiven for getting the impression from various sceptics, politicians and the like that the 'business as usual' use of fossil fuel energy is of no immediate consequence and even sustainable in the foreseeable future. The sky does not appear to be falling in. The sun comes up every morning and grandpa can recall far worse droughts, storms and floods as a kid than we are witnessing now. Non-scientific folks could be forgiven for thinking ‘yet another Y2K non-event’ or even a conspiracy when witnessing the weather patterns seemingly repeating themselves year after year.

From the other end of the spectrum some of us may be feeling that we are steadily following the dinosaurs' path to total extinction within decades as any international consensus and progress on greenhouse gas abatement agreements seems far from fruition, let alone put into practice, while being paid lip service in an endless round of international talkfests. We may be picturing in our minds the mass migration of populations from plague-, drought-, heat- and flood affected regions as ‘climate refugees’ search for areas across the globe that will support them in relative safety, and the territorial conflict that has historically followed such resource-scarcity events.

Regardless of which side of the fence you may currently be on, life continually exposes us to risk, which we all seek to minimise to some degree as a very natural function of our being. The case for Climate Change risk minimisation is pretty straight forward. Whether you think climate change is a real threat or simply a load of waffle, the best strategy to mitigate this risk is undeniably clear.

To clean up our atmosphere now will cost billions or even trillions for some nations. It will demand the end of some jobs but will create many, many others. If the expenditure turns out to be misplaced and the scientists are totally wrong, the worst outcome is that we may blow our budgets yet again amidst massive resistance from targeted fossil fuel industries and maybe finish up with another Global Financial Crisis or even a Great Depression. A daunting prospect indeed, but a situation which most of us would survive and we would, perhaps for the first time in history, achieve a level of global unity that would be unique in the history of mankind.

On the other hand if we carry on with 'business as usual' in continuing to burn an increasing amount of fossil fuels and the boffins turn out to be right, then what may be left of the human race is certain to be fully engaged in isolating itself from the environment that they inherited from previous generations in a desperate fight for survival. From the aspect of risk alone it doesn't take much mental exercise to choose between these two alternatives, and in common parlance, this exercise is a 'no brainer'.

'Yes', we do have an issue, possibly the biggest that homo-sapiens have ever faced, but 'Yes' we still have time to at least limit some of the damage, if not for ourselves but for our younger and future generations. That is, if we make the right decisions unilaterally; and act with due consideration for each nation's individual resources, financial status and well-being.

The reality is unfortunately that we humans are not investing sufficient attention to the problem which is getting more serious and costly to correct year by year. Commitments made by various government officials at one of the latest climate summit gatherings in Cancun all fall well short of

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i IPCC AR5 Working Group 111 item 1.3.3- a term used by the International Panel on Climate Change IPCC which assumes that future development trends follow those of the past and no changes in policy will take place.
the mark and if implemented would represent a total waste of effort, resources and especially time. Our current addiction to the convenience of fossil fuels which are involved in practical every phase of modern living will be an immense 'habit' to kick. But this is something we must do regardless - or our newer generations will be faced with a truly impossible task and an extremely challenging future. To paraphrase environmental activist Paul Gilding; “… we have been indulging in a massive ‘Ponzi’ scheme whereby we are depriving future generations of their environmental heritage”

What is clear is that in order to mitigate the risk of Climate Change over the next decade we are now faced with making considerable changes in our energy-generation patterns. Unfortunately the fact remains that we humans, and most of the mammalian species, have evolved under very different climatic conditions than those we now appear to be rapidly heading towards and which will dominate the climate for thousands of years.

Prior to the industrial revolution that began in the mid-18th century CO₂ concentrations were a low 280 parts per million by volume (ppmv), a level they had been for the previous 650,000 years. Current levels are estimated to be around 396 ppmv. The last time the earth witnessed CO₂ concentrations above 396 ppmv was in the mid-Pliocene era, some 3 million years ago, when average global temperatures peaked out at somewhere between 2⁰ C and 3⁰ C higher than today, with sea levels finishing up around 25 metres higher than we have now. Of course we weren’t around then and scientific references to what has happened in the past are not always indicative as to what we are facing now - as nature makes its own rules.

In the 650,000 years prior to 1750 the average global CO₂ levels did fluctuate due to a number of natural factors like orbital cycles of the earth, volcanic action, meteor impact etc., but never higher than 287 ppmv. We are now approaching 400 ppmv CO₂ and rising at over 2 ppmv per annum.

2 The end of growth: No denying this giant Ponzi scheme. Paul Gilding 17th Feb 2012

Not one of us has ever experienced a global average temperature rise of 1\(^0\) C or 2\(^0\) C that is the target for current Climate Change negotiations, let alone a 4\(^0\) C rise that some scientists suggest we are heading towards. Exactly how we will endure as a species in these uncharted waters we can only speculate, but it is certain that life will be far more precarious for much of the life currently inhabiting the planet.

Some of us may feel the necessary adaptation will be all too hard. Others may feel that the earth is on the brink of yet another mass-extinction era. Most of us hopefully are optimists and we can rise to the challenge and are prepared to make the necessary sacrifices. Throughout the world what is needed most urgently is for our leaders and policy-makers to focus unswervingly on this task … no matter what! Making the right choices and not charging off on some time-wasting program of energy reforms is paramount. And making the right choices is becoming rather urgent in view of the lead times involved in such a major restructure of our energy infrastructure.
Part 1: The current situation

“One of the biggest obstacles to making a start on climate change is that it has become a cliché before it has even been understood”
— Tim Flannery,

1. Climate Change – the euphemism for Climate Breakdown

The climate has changed many times over the millennia but nothing like as rapidly as is happening now. An insidious aspect of any such disruption is the presence of most greenhouse gases by and large cannot be witnessed by any of our five senses alone, similar to the case of nuclear radiation. Carbon Dioxide (CO$_2$), Methane (CH$_4$) and Nitrous Oxide (N$_2$O) are colourless gases and our noses cannot sense their odour in such atmospheric concentrations that adversely increase global temperatures, concentrations which incidentally seem relatively minute compared to the 99% of the main components of the air we breathe namely, Nitrogen (N$_2$) and Oxygen (O$_2$).

Water vapour (H$_2$O), itself a greenhouse gas amplifier (i.e. a strong positive feedback component (that increases the impact of greenhouse gases) is both invisible and odourless but can be sensed at times of high humidity. And clouds themselves which are made up of condensed droplets of water, are an historical record of the vapour having been present. Clouds, a product of atmospheric water vapour, are one of the great unknowns in the predicted impact of Climate Changes as they can have both positive and negative impact on warming, depending on their height above the earth. The big difference between water vapour and other greenhouse gases is that it does condense quickly dropping out of the atmosphere as rain.

Current estimates of the average global temperature is determined by the amalgamation of information from thousands of meteorological stations, satellite information and ocean surface and underwater measurements taken around the globe on a regular basis.

There is also the common use of the word ‘carbon’ to refer to carbon dioxide such as Carbon Tax, Carbon Accounting, Carbon Budget, carbon credits etc., but they all refer to CO$_2$. Although this is not the most potent greenhouse gas, it is certainly the most common and fastest growing one in our atmosphere at present and so the main one we have to worry about.

Now any of us should be excused if we are totally baffled by the International Panel on Climate Change’s (IPCC’s) reports as they are written by scientists in scientific parlance. Even their various Summary for Policymaker documents seem to be no exception and there must be doubt as to whether many of our policy makers have read them through let alone understood them. The IPCC none the less have been doing a great job and no one will ever be able to seriously claim that they have not given us ample warning of the problems we now face. There are so many scenarios and conditions that IPCC have had to take into account; like exactly what our future emission patterns will be, how much forest removal there will be, where and what their final impact will be on the climate, how quickly the whole world will react to the challenge, what natural events will take place etc., may just leave some of us confused as can be witnessed in the media.

The crux of their statements as far as we see it is for the world to limit the total emissions to 450 parts per million by volume (ppmv) CO$_2$eq by 2100 in a bid to limit the global average increase to 2$^\circ$ C over the balance of the century. This unfortunately will not get us back to pre-industrial levels but it will minimise the impact of Climate Change to levels that could be dealt with through 'climate
adaptation' and allow us to retain some of the climatic conditions humans and most mammals have evolved in. IPCC’s definition of CO\textsubscript{2}eq in the case means the carbon dioxide of all the long lived greenhouse gases plus the impact of deforestation, possible cooling phenomena like aerosols etc.

If we go to 500 ppm CO\textsubscript{2}eq by 2100 and no higher there is reasonable confidence that we will stay below 3\textdegree C which will have greater consequences but not quite bring on Armageddon. If we overshoot the 500 ppm mark before 2100 we will be faced with having to attempt to extract CO\textsubscript{2} and methane directly out of the atmosphere and ‘landfill’ it in certain geological strata at high pressure. This process will be costly, use considerable amounts of clean energy, require a need to be monitored for centuries and it will not be without risk (for more detail Appendix 5).

Annually recorded greenhouse data available in the media and on the internet usually only includes CO\textsubscript{2} or sometimes the main long lived greenhouse gases, so if we see that we are already at 481 ppmv CO\textsubscript{2}eq\textsuperscript{2} we may think we have ‘blown it’ already. Well, not quite yet hopefully.

So what all this about; a 2\textdegree C warmer threshold we are told we must avoid? We are concentrating on the IPCC results being from the expert body in this field, here in this document. The IPCC was been commissioned to study the Climate Change problem in 1988 under the auspices of the United Nations.

There appears to be a plethora of ideas and misunderstandings on the 2\textdegree C warmer subject in the literature from doubling of CO\textsubscript{2} content in the atmosphere to twice the pre industrial age level (pre 1750) of around 287 ppmv to 574 ppmv. Others claim 450, 550, or 560 and so on. As mentioned there is also some confusion as to actual entities being measured like just CO\textsubscript{2}, CO\textsubscript{2} plus all long lived greenhouse gases (labelled CO\textsubscript{2}eq for Carbon Dioxide equivalent). The IPCC's definition also allows for entities like land clearing and degradation (albedo), dust, aerosols from volcanic action etc. To add to the possible confusion as well as ppmv limitations there are also those for carbon mass in Giga tonnes (Gt) and Petra grams (Pg) of carbon or CO\textsubscript{2} or CO\textsubscript{2}eq. For information tonnes of carbon can be converted to tonnes of CO\textsubscript{2} by multiplying by a factor of 3.664. That's right. Each tonne of carbon inherent in varying degrees fossil fuels that is burnt creates almost 3.7 tonnes of CO\textsubscript{2}.

For the benefit of clarity we will label the IPCC's figures as CO\textsubscript{2}eq (IPCC 2014) in this document as representing what the IPCC refers to in its latest 2014 report.

What this boils down to is that to allow a reasonable chance (66% and above) of us staying within the 2\textdegree C increase we need to:

- limit emissions to 450 ppmv CO\textsubscript{2}eq (IPCC 2014) by 2100 (the reading as of 2011 was 430 ppmv)\textsuperscript{3} or

- no more than a total of 2,900 GtCO\textsubscript{2} (Please note CO\textsubscript{2} and not to be confused with CO\textsubscript{2}eq by any definition), a limit which also allows for the other greenhouse gases. Within the period from around 1870\textsuperscript{4} to 2011 we had released 1890 GtCO\textsubscript{2}.

There is actually a range of uncertainty plus and minus on all of these figures. So we can say as of 2011 we had around 20 ppmv CO\textsubscript{2}eq (IPCC 2014) or 1010 GtCO\textsubscript{2} in the Carbon Budget left to spend.

Now a 2\textdegree C increase in the global mean temperature may sound trivial to some of us as we regularly...
witness a swing of 20°C or more in a day. But we are not talking daily weather patterns here. The 2°C increase in average atmospheric temperature means a whole lot more thermal energy that our atmosphere will need to absorb and dissipated somehow in mechanisms such as wind patterns and ocean currents, evaporation and precipitation, flooding and drought. The limits of the temperature extremes will also increase.

The last time our species (Homo sapiens) witnessed a 2°C increase was 120,000 to 130,000 years ago. It is only left to our imagination as to just how many survived the impact.

The National Oceanic and Atmospheric data Centre (NOAA) advise that the increase in average combined (land and ocean) global temperature over the November 2015 was already 0.97°C above the 20th century average of 12.9°C. The CSIRO say Australian sea surface temperatures have increased 0.9 C deg since 1900. Oceans take longer than land masses to warm up and cool off so it’s a case of watch this space. Year 2014 and now 2015 were the hottest years on record and 2016 may hold a trump card. Approximately 50% of the total emissions since 1750 to 2010 occurred in the last 40 years.

Our guess is, if you have read this far then you will be thinking ‘We should have been dealing with this problem several decades ago.’

This, of course leaves us with a massive challenge seeing we are currently increasing CO₂ levels alone by more than 2 ppmv per year as a result of an increase of more than 2% GtCO₂ pa emissions in recent years.

Now as we do not seem to have regular annual feedback on CO₂eq (IPCC 2014) emissions perhaps due to its complexity but from a start of 430 ppmv in 2011 and a rate of growth of 2 ppmv pa it doesn't take a mathematician to realise we will reach the 450 ppmv limit in less than two decades at the current business as usual pace.

For those who wish to do the sums it seems to be more appropriate to use IPCC’s proposed limit on the mass of emissions (GtCO₂) that we can safely emit to meet the 2°C increase criteria. Annual emissions are published by various groups on the internet and elsewhere and freely available to the public, albeit perhaps one or two years in arrears. To mention a few we have the European Commission's EDGAR, the independent consulting group Enerdata, British Petroleum's Statistical Review of world energy – Data workbook and World Bank's World Development Indicators. One that we chose (Global Carbon Budget Organisation's spreadsheet 2015 Version 1.1) indicates that together with land use degradation of 4 GtCO₂ pa in total we are emitting just under 40 GtCO₂ pa at an average increase rate of 2.15% pa. Our derived figure for the remaining Carbon Budget giving us a better than 2/3rds chance of staying within the 2°C global temperature increase as of January 2016 is 850 Gt CO₂. At the present rate of emissions this will disappear by 2033. It is also all we have left to completely replace fossil fuels as an energy source.

One scientist in particular, Michael Marr, gives us a bit longer claiming we will pass a 2°C threshold as early as 2036 if we persist in burning more and more fossil fuels as at the present BAU scenario.

Another scenario to give us better than an 80% chance of success has been put forward by the London based not-for-profit group Carbon Tracker Initiative which determines a Carbon Budget figure of 565 Gt CO₂ left to spend between 2010 and 2050. Needless to say this option gives us even less time to get things sorted.
New alternative energy power plants can take 10 years or more to plan, build and commission. Procrastination is no longer an option.

Now sceptics might immediately claim that 40 GtCO$_2$ pa is nothing compared to the amount natural amounts of CO$_2$ alone which are emitted each year. Well that statement is true but only half the story. The Earth also retrieves the same amount in vegetation (photosynthesis) and absorption by the oceans each year. What we are talking about is additional to what nature has dealt with for millennia.

So again it can be reasonably assumed, however we interpret the scientific data, we have little more than one or two decades to get it right.

![Image](ClimateChange.gov.nz)

Some of the sunlight is reflected back into space by the atmosphere, high level clouds or the earth surface itself. Other sunlight is absorbed and reflected back with a change in wavelength into the infra-red spectrum. Greenhouse gases first absorb this and then re transmit but in all directions rather than directly up into space. Hence half this radiation heads back toward the earth surface and back again in a constant shuttle manoeuvre. In pre-industrial times this phenomena kept the earth at very tolerable temperatures. Without greenhouse gases being present in the atmosphere the earth global average temperature would be an intolerable minus 18$^\circ$ C. But now we are heading in the opposite direction with increasing global temperatures beyond anything our species, and most others on the planet have ever experienced.
What should be abundantly clear to us all, although ignored or dismissed by many in one form or another, is that we already have a sizeable problem on our hands to solve in pushing for change and despite promising International agreements in the UN Climate Conference in Paris late 2015 we haven’t even got a plausible game plan in place that will ensure we can transform the energy sector globally within the constraints of the Carbon Budget. Failure to change direction is not an option. As the UN’s International Panel on Climate Change (IPCC) point out, we are heading for a long lasting increase in average global temperature in the order of $3.6^0$ C.

Let those that wish to deny the whole issue have their rights of freedom of speech but meanwhile let the rest of us get on with the challenges ahead. 'No', this situation is far from hopeless, but we must stop the vacillations and just get on with the job. We need to focus the politicians and policy makers of this world and Australia has major reasons to be seen leading the charge.

![Graph showing emissions](image)

Fig. 1.2 - What we need to do in a nutshell. The need for radical change to our ingrained habits is urgent and paramount. The fossil fuel party is well and truly over. Each year of procrastination increases the cost and decreases our chances of success.
“Energy is liberated matter, matter is energy waiting to happen.”
— Bill Bryson, A Short History of Nearly Everything

2. The Energy we currently use.

2.1 Basics

Perhaps other than during the cold war when mass extinction threatened to start at any time with a four minute warning, never before in our recorded history have we faced what some would describe a 'Perfect Storm' of confrontations including unprecedented world population growth, rampant consumerism, Climate Change, diminishing resources, resistance to change, coupled with the desire for us all to have first world type prosperity.

It is natural to assume somewhere in the near future serious adjustments to current concepts have to be made if we are to avoid ever escalating conflict over resources, be it arable land, fresh water, food, energy or simply just a manageable local climate.

Put simply it all comes down to energy demand, and where we are heading is basically what this document attempts to address by putting forward how we are meeting our current and growing demands and what we must consider as workable options for the not-too-distant future. What do we mean by energy? Well there's primary energy or energy that is found in nature, which has not been subject to any conversion or transformation. It can be renewable such as electricity and/or heat from solar and geothermal primary energy but also non-renewable, which is what we have been mainly drawing on for the last 200 years or so, such as chemical energy found in coal, oils and natural gas. A secondary energy such as electricity, is currently generated by converting chemical energy mainly from fossil fuels like coal, gas, and oil and to a much lesser extent by conversion of renewable energy such as solar, wind, geothermal, hydro, timber plus, in many countries, from nuclear fission energy. Energy derived from batteries, combustion of molecular hydrogen and that from back up heat sinks adapted by the likes of solar and wind farms can be regarded as tertiary energy and they are usually derived from both primary then secondary sources.

There is also energy we use in transport, road, rail, sea, and air travel which is usually acquired by converting the primary (chemical) energy contained in fossil fuel petroleum products like oil, petrol (gasoline), liquid petroleum gas (LPG), aviation spirit and diesel fuel into mechanical energy.

The laws of physics state we will never get 100% conversion from the use of primary energy. There are always some losses to other forms of energy. For instance the chemical energy stored in coal seldom converts to more than 48% electrical energy and usually much less. Much of the energy is lost as heat, plus to a lesser extent light, sound and unwanted chemical exchanges. The ubiquitous internal combustion engine (ICE) found in most vehicles today, while more efficient today than ever seldom exceed 37% and that used to actually propel the vehicle, after generator, air-conditioner and accessory demands, is often much less.10

Now, as most people are familiar with the energy unit Kilowatt Hours (kWh) i.e. the units of consumption we are charged in our electricity and sometimes gas bills, it seems the most appropriate energy unit to use in this document wherever possible. Sometimes the number get so big it is more appropriate to use Megawatt Hours (MWh), Gigawatt Hours (GWh) or even Terawatt Hours (TWh) i.e. thousands, millions and billions of kWh respectively. The kWh is not a Systems International (SI) unit for energy, which is the Joule, but it seems more familiar to most folk. In

Page 12
terms of power capacity a power station’s capacity of say 500 Mega Watts (MW) means it is capable of providing 500,000 kWh per hour of electrical energy. Should you need to convert these or other units to some that you find more familiar then there is a glossary at the rear (Abbreviations & Conversion Factors) to assist.

According to British Petroleum’s data, currently the top twenty most energy ‘indulgent’ countries (which include countries such as Australia, Canada and USA), average just over 79,000 kWh/capita/annum whereas the bottom twenty, less fortunate countries average just around 10,000, kWh/capita/annum - or just under 12.6% of the average of that of their rich global neighbours.\(^{11}\)

The top twenty energy hungry countries represent a total population of approximately 537 million or just 7.2% of the world’s population.

British Petroleum (BP) Statistics also indicate world primary energy consumption per annum for 2014 to equate to over 150 trillion kWh p.a. of primary energy per year, including that which is used to generate electricity. Of this 86% is due to burning of fossil (coal, oil & natural gas) fuels and this percentage is also growing at around 2% pa. It is interesting to note that world primary energy consumption grew over 5 fold between 1950 and 2010 while world population only increased less than three-fold\(^{12}\). Over the same period fossil fuel primary energy increased over 6 fold. The break-up of this primary energy use into sectors is shown in Fig 2.1.

![Global Primary Energy Consumption 1830 - 2010](https://www.theoildrum.com)

**Fig. 2.1:** Our insatiable need for energy. Courtesy: The Oil Drum. Since shortly after the Second World War there has been an unprecedented demand for more primary energy consumption far out-stripping the growth in population. Fossil fuel usage continues to far outweigh that of renewables and nuclear.
Even imagining without the world population increasing to 10 billion this century\textsuperscript{13} or without those developing countries aspiring to First World energy usage we have a major challenge ahead to phase out the use of fossil fuels well before we burn up the balance of the Carbon Budget. Options of how we go about that are limited to renewables (Direct Solar, Wind, Tidal, Wave, Hydro, Biomass, and Geothermal), nuclear fission (current nuclear generation techniques) and most hopefully, yet unlikely to be ready in time, aneutronic nuclear fusion (still in its development stage – see chapter 12).

Australian primary energy for 2013-2014 was stated to be 1.62 trillion kWh\textsuperscript{14} or a bit over 1\% of world primary energy consumption while its population represents just over 0.3\% of global. Some 95\% of this energy was fossil fuel based. This break-up is shown in Fig. 2.3.

But Australia also exports much more in the way of fossil fuels and in 2013-14 this amounted to the equivalent of 3.47 trillion kWh\textsuperscript{15}.
So where do we go from here? We humans are somewhat caught up in a dilemma in as much as while we need to wean ourselves off fossil fuels as quickly as possible there is also the substantial inertia to do so by way of:

- The economic lifetimes of current fossil fuelled power stations and transport vehicles that are fossil fuel dependent such as cars, ships, aircraft.
- Political will and cooperation of the world's leaders.
- Proposals such as *Why us*
- Preference for energy security by way of local resources
- Population growth pressures
- Consumerism addictions
- Substantial resistance and lobbying by the fossil fuel fraternity
- Perceived national priorities e.g. 'distractions' like Gross Domestic Product (GDP) growth (especially that related to fossil fuels), votes, protection of outdated fossil fuel jobs over global welfare issues, the here and now- all of which are last century’s top priorities. Of course these are all still important and we must not ignore increasing threats from radical groups but unless we address Climate Change now, and with absolute determination, these
other issues will become irrelevant.

2.1 Less carbon rich fuels

One means of reducing the amount of CO\(_2\) produced by the combustion of fossil fuels is to use a less carbon intensive fuels such as Natural Gas - which is mainly methane (CH\(_4\)). This gas has the advantage that there is a substantial amount of hydrogen, which has a very high calorific (heat) value compared to carbon. Weight for weight hydrogen will generate 4.4 times as much heat as carbon (graphite) which is the main constituent of coal. Unfortunately it is not found to any extent in its free state un-combined with other elements on earth. Australian natural gas, weight for weight, generates 2.1 times the heat from the equivalent weight of black coal. Methane is therefore regarded as an interim fuel in our disengagement with fossil fuels (see Table 2.1). Methane however released directly into the atmosphere without being burnt has a far greater impact as a greenhouse gas per molecule than CO\(_2\) and its concentration in the atmosphere is growing. However, as mentioned earlier the sheer volume of CO\(_2\) makes this the main threat, at least for the foreseeable future.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Lower calorific value (LCV) MJ/kg</th>
<th>Heat value (lower calorific) kWh/kg</th>
<th>kg CO(_2) released per kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>120</td>
<td>33.33</td>
<td>0</td>
</tr>
<tr>
<td>Natural gas</td>
<td>50</td>
<td>13.89</td>
<td>0.214</td>
</tr>
<tr>
<td>LPG</td>
<td>46</td>
<td>12.78</td>
<td>0.23</td>
</tr>
<tr>
<td>Carbon (graphite)</td>
<td>32.8</td>
<td>9.11</td>
<td>0.40</td>
</tr>
<tr>
<td>Petrol (Gasoline)</td>
<td>41.2</td>
<td>11.44</td>
<td>0.256</td>
</tr>
<tr>
<td>Diesel</td>
<td>43.4</td>
<td>12.06</td>
<td>0.27</td>
</tr>
<tr>
<td>Thermal (black) coal</td>
<td>26.1</td>
<td>7.25</td>
<td>0.32</td>
</tr>
<tr>
<td>Brown coal (lignite)</td>
<td>5.8 – 11.5</td>
<td>1.61 to 3.19</td>
<td>0.31</td>
</tr>
<tr>
<td>Wood (dry)</td>
<td>17</td>
<td>4.72</td>
<td>No fossil GHG</td>
</tr>
</tbody>
</table>

Table 2.1 Approximate comparison of fuel primary heat values and emissions. As you will note there is a considerable saving in CO\(_2\) emissions by using natural gas compared to coal. GHG emissions from hydrogen are zero if burnt as part of a fuel such as natural gas or kerosene. But much energy has to be exerted to obtain free, un-combined hydrogen and hence does have a substantial emission footprint if fossil based energy is used to obtain it. Note: LCV or Lower calorific value is the total heat value less the heat of vaporisation of water vapour contained as this is not often recovered in practice.

While it can be seen from Table 2.1 that emission rates for brown coal (lignite) as used in Victorian power stations may generate slightly less CO\(_2\) per heat unit than thermal (black bituminous) coal used in NSW and elsewhere, when it comes to the actual emissions in regard to the electrical energy output (kWh\(_e\) as opposed to the primary energy inherent in the fuel kWh) Table 2.1 figures must be divided by the efficiency of the specific power station. Figures provided by Australian power station operators to the Clean Energy Regulator often show a much more diverse situation in practice (see Appendix 2). While thermal coal fuelled power station emissions range between 0.74 and 0.92 kgCO\(_2\)/kWh\(_e\) those of Victoria’s brown coal stations range much higher. For example Yallourn, Hazelwood and the now mothballed Energy Brix emitted 1.35, 1.41 and, according to one

You would think that these facts alone would stir up Australia's political leaders to dynamic action. Sadly not necessarily the case while anything along those lines may affect the all-important popularity poles.

We examine some of our options in the following chapters. To quote author Scott L Montgomery ‘The task is to harness the best of these, without poisoning the planet or inspiring new realms of conflict and war’

As shown in Fig. 2.2 the fossil fuel portion of world primary energy is 86.3% of the total. Oil figures also include petrol, diesel and aviation fuel. Suitable dam sites for hydro electricity generation are becoming scarce and often involve disruption and problems especially when diminished downstream flows cross sovereign boarders. Any reduction in river levels in one nation brought about by other nations dams upstream will likely be a point of dispute. Deployment of renewable energy sources is increasing world-wide but solar and wind generator operations are governed by the fickle nature of weather and so far do not provide round the clock base load energy although some use heat banks or batteries that can last up to 15 hours and others even have natural gas back-up units. After decades of stagnation, the nuclear option is seen as a means of replacing fossil fuelled power stations, particularly in China with its dense population and growing demand.

While the risks of poor safety analysis on nuclear plants in the past has brought the industry into dispute, the alternative risks of unchecked Climate Change are limitless. What is of real concern is the rate of primary energy growth per capita, much of which is being met by fossil fuels.
“We've never seen anything like this scale of bleaching before. In the northern Great Barrier Reef, it's like 10 cyclones have come ashore all at once”

Professor Terry Hughes – James Cook University

3. What is starting to happen?

While it is currently difficult to distinguish normal weather patterns from those that have been influenced by Climate Change, there is growing evidence that at least extreme events are being manipulated accordingly.  

3.1 Sea level change.

The National Aeronautics Space Administration NASA monitors many phenomena by way of its satellite activities, one of which is sea level rise that has been measured 36 times a year since 1993. Their graph of Global Mean Sea Level (GMSL) is shown in Fig. 3.1.

Fig. 3.1 - NASA's sea level rise 1993 to Sept 2014. Since 1993 to September 2014 there has been a 56.35 mm height increase in sea levels globally rising at 3.17 mm per annum due to both thermal expansion and melting land based ice and snow. Australia’s CSIRO have also been tracking sea level rise using coasted tidal gauge data since 1880 (Fig 3.2)

![Global Mean Sea Level (GMSL) - 1880 to 2012](image)

Fig. 3.2 Global mean ocean levels since 1884. Courtesy: CSIRO
2.2 Global mean temperature

NASA’s Goddard Institute of Space Studies, along with many other prestigious institutions have also been tracking global temperatures. As of late 2015 the increase was 0.87°C above 1951 – 1980 average temperatures.\(^{17}\) (see Fig 3.3)

![Graph showing temperature anomaly over years](image.png)

Fig. 3.3 NASA’s combined land-ocean temperature index – Now at +0.87°C relative to 1951 – 1980 average temperatures.

The ten warmest years in the 134 year history of these records have been since 1998 - and 2015 was the hottest on record. El-Nino played its part in 2015 - but watch this space.

2.3 Arctic & Antarctic ice sheets

In 2007 researchers discovered that the year round ice pack of the Arctic have lost 20% of its mass in just 2 years. While losses of ice sheets in the Arctic does not contribute to sea level rise, as they are already displacing the sea water, their extensive reduction in recent decades has opened up water’s much less reflective surfaces to sunlight which results in even more heat absorption. Ironically some of the big oil and gas companies are clamouring for new leases in the region in order to grab more fossil fuel reserves.

Antarctic ice has from time to time increased in area for reasons so far unknown but the gain is far less than the Arctic ice losses. A 2014 NASA report\(^{18}\) calculates the combined Arctic and Antarctic ice area trend between 1979 and 2014 has decreased at the rate of 1.47% pa and there is evidence that the Arctic ice is also becoming thinner.

2.4 Ocean acidity

Much of the excess CO\(_2\) is being absorbed by the ocean which in turn is causing acidification. As you may know sea water is normally slightly alkaline. The high concentration of Calcium Carbonate (CaCO\(_3\)) minerals normally in seawater is needed to build skeletons and shells of various forms of marine life, corals etc. Since the Industrial Revolution the alkalinity has decreased due to additional CO\(_2\) adsorption by approximately 0.11 pH units which doesn't sound a lot but as the pH scale is logarithmic a 1 pH change is a factor of 10 larger than its initial value. In other words the ocean becomes slightly more acidic. The 0.11 pH increase correlates to approximately 30% increase
in acidity. This phenomenon reduces the amount of carbonate ions in the water and hence the ability for invertebrate marine life to create their basic building blocks

What the full extent of this will be is yet to unravel but it is not likely to be good news and if the trend continues unabated it is likely devastate most of our remaining seafood resources, corals etc.

A scientific aerial survey of the Great Barrier Reef early 2016 has determined an unprecedented 93% has now been hit by bleaching due to warming sea water and lower pH.

2.5 De-forestation

The natural ability for forests and plants to absorb CO₂ and emit O₂ is common knowledge and hence the reduction in the amount of this amazingly helpful entity is to our disadvantage.

The United Nations Food and Agriculture Organisation (UNFAO) estimated between 2000 and 2010 we lost 5.2 million hectares (52,000 sq kilometres) of forest per year mainly due to agriculture expansion, logging and urban expansion. An interesting observation is that between 2005 and 2010 while Australia and Brazil have each been deforesting at the rate of 500,000 hectares per year China has been increasing its forest area by the same amount.

Fortunately there has been a reduction in this deforestation figure since 2010 but overall since 1990 we have lost an area of forest equivalent to almost the size of South Africa (That's 120 million hectares, or more than the area of NSW, Victoria and Tasmania combined).

While the globe's land area still has about 30% forest these losses amount to a decrease in CO₂ sinks accounting for about 10% of annual global emissions.

Fig. 33 A vivid depiction of the Brazilian rain forest conversion.
2.6 Fauna under threat

The World Wildlife Fund (WWF) advise that several species are being threatened by Climate Change and associated human activity. It estimates 30% of species are being threatened with extinction with a 2 -3°C increase in global temperature\(^2\). There is also evidence that fish species are moving away from their normal habitats to cooler waters. Fish species normally in the North Sea off the south coast of the UK are now seen off the coast of northern Scotland. Other species are also heading south in Australia\(^2\).

Australian Government's Great Barrier Reef Marine Park Authority have advised 1600 species of fish on the reef are under threat of Climate Change due to increase temperatures, acidification and excessive sea level rise over traditional breeding grounds. Coal export facilities planned in the region will no doubt accelerate this decline.

2.7 The Gulf Stream

While yet to be fully studied there is growing concern that the warming of the oceans may have a direct impact on the so called thermohaline system of ocean currents and in particular the Gulf Stream that keeps northern Europe reasonably comfortable in winter (an estimated 5°C warmer). The IPCC has suggested the Gulf Stream may slow down this century. One of the sources that drives the northward path of this warm water system has reduced by 20% since 1950. And another report suggests that calculations of quantities of warm water flowing north had reduced dramatically in recent years but so far there are no symptoms of lower temperatures on land.\(^2\)\(^5\) Ironically should this occur at the appropriate time it will ensure that temperature rise in northern Europe due to Climate Change may not be a severe as other parts of the continent.

Glaciers are retreating, humidity in increasing, snow fields are shrinking etc., more on this topic in Appendix 3.
4. How do we know it’s us?

4.1 What is not causing Climate Change

One of the best ways to review what is not causing the concern about Climate Change is to check out the climate denier's blogs and such. One has to admire the various authors’ tenacity and shear guile. The study of the psychology of this denial phenomenon is a whole other subject again which we plan to discuss at a later date. But one of the best ways to learn the true facts about Climate Change is to examine all the denier’s claims in detail. Interestingly one of the best websites devoted to debunking some of the denier's claims has itself been called http://www.skepticalscience.com/

Examining but a few claims:

The half-truths:

Claim 1. The climate has changed continuously over the millennia and so it is again.

Correct but there were proven natural incidents and reasons such as massive volcanic activity, meteorite impacts, Milankovich orbital variations and such. The global temperature levels danced in tune to the associated CO$_2$ and methane level variations and vice versa in much the same way as today. CO$_2$ levels have been very much higher and lower than they are at present but then mostly we weren't around. Some changes took millennia and flora and fauna generally evolved accordingly. Other changes were very rapid as per today and there was often a resulting mass extinction.
Fig. 4.1: The Deuterium (an isotope of hydrogen) concentration is just one of the fingerprints used to determine ancient temperatures in ice cores. Close correlation between CO₂ (in blue), methane (in green) and temperature (in red). There is a total of five ‘highs’ in the last 420,000 years. The natural global orbital (Milankovitch) cycles however do not follow the same trends. Courtesy: Arctic News

Fig 4.1 shows the previous time mankind witnessed 2°C to 3°C global temperature increase was around 120,000 years ago when we Homo sapiens were a relatively infant species. All past peaks to the current one can be attributed to natural causes. Not so the present one. Some folks argue that temperature drives CO₂ atmospheric concentration and this time it’s the other way round. That claim is not evident in this graph and in fact, they both influence one other.

Methane (CH₄) makes up the larger portion of what is sold as ‘natural gas’. Fig 4.1 also shows much of the changes in temperature in the past 420,000 years are well correlated with methane levels. It only rates second place in the cause of the present warming phenomena because of its present low atmospheric concentration. This concentration however is on the increase although since 1990 the increase this has slowed for some yet unknown reason to around 1.77 ppmv. Some of the methane escaping to the atmosphere currently comes from natural sources such as wetlands.
and microbe (such as in termite) digestion forming part of the balanced natural cycle. But it is also generated human intervention in landfills where organic waste decays, ruminating animals such as cattle and sheep which discharge a considerable amounts.

There is growing concern that a warming global temperature may be starting to release massive quantities of such 'fossil' methane gas from ancient sinks in the Siberian tundra and ocean depths.

Claim 2. Water vapour is the most virulent greenhouse gas.

True again but as mentioned earlier it, water vapour mainly acts as an amplifier or feedback entity on the overall 'clout' of other greenhouse gases. Unlike the long lived greenhouse gases its atmospheric life cycle is short. In pre-Industrial times, when CO$_2$ levels were under 287 ppmv the leveraged impact of water vapour would have been far less.

Claim 3. The sun spots are the cause.

Apparenetly the additional irradiation (especially extreme ultra violet radiation) during sun spot activity does have an impact on the climate but not necessarily in any uniform way that could result in an increase in global temperature. Rather it tends to be more regional and has more influence on rainfall and storm patterns than actual temperature increase. In fact there is evidence of actual cooling of the eastern Pacific Ocean regions during the peaks of the sun’s 11 year solar cycle$^{27}$. The conclusion of the report 'The Effects of Solar Variability on the Earth's Climate' by the National Research Council's (NRC) is in line with that of the IPCC i.e. solar variability is not the cause of global warming over the last 50 years.

For a more precise and complete analysis on this subject go to the Barrett Bellami site http://www.barrettbellamyclimate.com/page48.htm

Claim 4. ‘Yes’ it could be us causing Climate Change but what difference does Australia’s small population make world-wide?

According to the International Energy Agency (IEA) their 2011 figures show Australia’s overall annual emissions were greater than those of the 60 poorest countries combined, with a total population of over 1.1 billion. Also per capita, Australia emitted over three times as much as each Chinese person. In 2011 Australia has had the dubious distinction of out-performing the USA on a per capita emissions basis. More recent figures (2014) extracted from BP's Statistical Review Australians now rank 18$^{th}$ in the world's per capita energy consumers behind the Organisation of Economic Cooperation and Development (OECD), countries of Canada (11$^{th}$), South Korea (16$^{th}$), Norway (12$^{th}$), Sweden (17$^{th}$) and United States (14$^{th}$).

Claim 5. Yes it is us but what can I possibly do about it?

In a democracy we all have a vote and the right of free speech. Regardless of which political party is favoured they gain election by voters. We can all divest interest in company shares that invest in fossil fuels e.g. banks and their credit cards despite the 'waffly' rationale they may bombard you with. We can all be more energy conscious and reduce our 'waste'. We can examine our list of wants and rationalise our real 'needs'. We can check out on-line and offset our carbon footprints. There are a number of on-line calculators and options to offset such as The Carbon Neutral Charitable Fund www.enef.com.au to mention just one.
4.2 Positive signs of human intervention

The correlation between the CO\textsubscript{2} estimated to have derived from fossil fuels combustion and the growth of CO\textsubscript{2} in the atmosphere since 1900 is 99.9%\textsuperscript{28} (Fig 4.2)

![Graph showing correlation between carbon emissions and CO\textsubscript{2} ppmv count, r = 0.999](image)

Fig 4.2 Correlation between our emissions and the CO\textsubscript{2} ppmv count is 99.9%. Courtesy: Barrett-Bellamy. A brilliant piece of mass balance work showing what fossil fuel we have burnt compared to the change in CO\textsubscript{2} content in the atmosphere

Further, what has been identified as being a most conclusive fingerprint of the impact of increasing fossil fuel CO\textsubscript{2} in the atmosphere are the changing ratios of carbon isotopes. The element carbon has two stable isotopes namely \textsuperscript{12}C (at 98.9%) and \textsuperscript{13}C (most of the remaining 1.1%). There is also a radioactive isotope of carbon \textsuperscript{14}C with a half-life of 5,730 years that is generated by the impact of cosmic rays in the upper atmosphere on \textsuperscript{14}N (the isotope making up 99.6% of Nitrogen).
Fig. 4.3 Three different isotopes of carbon. By way of explanation isotopes of any element act identically in chemical reactions but contain more or less the same number of neutrons (neutrally charged sub-atomic particles) in their nucleus from each other, which determines their differences in mass and physical and nuclear reactions. The half-life of radioactive isotopes refers to their time to decay to half their radioactivity level from their original value.

Now we know the atmospheric ratios of $^{13}$C and $^{14}$C are gradually falling in relation to $^{12}$C. And in the case of $^{13}$C this means the newer emissions will have come from either fossil fuels, burnt vegetation or both. The photosynthesis mechanism of plants known as the Suess effect ensures that plants will take up less $^{13}$C than $^{12}$C relative to the ratio in the atmosphere. As animals consume plants they too have the same isotopic carbon ratios. Once they die the $^{14}$C isotope decays so that after thousands of years the $^{14}$C readings can be used to determine a sample's original age (the principal used in carbon dating).

Fossil fuels, which were formed some hundreds of millions of years ago were once living organisms. The prominent type of plants and creatures that ate them in those periods where even more depleted in $^{13}$C than plants living today so the $^{13}$C fingerprint of CO$_2$ from fossil fuel emissions is identifiable. Further, the fossil fuel's $^{14}$C radioactive isotope has had thousands of half-lives to decay and thus is virtually non-existent in fossil fuel samples today. Hence a depleted $^{13}$C
and $^{14}$C isotope types of CO$_2$ in the atmosphere can only point to them originating from recent combustion of fossil fuels. Conclusion: “It’s us...and we are not just heading for the rocks, we are now in amongst them with no one really at the helm.”

Fig 4.4 showing depletion of $^{13}$C in our atmosphere as CO$_2$ content has increased. Courtesy: CSIRO. Here the clear message of human impact on the climate as the Carbon isotope $^{13}$C is depleting as it was not so common in plants from which fossil fuels are derived.
“Men argue, nature acts” Voltaire

5. The big clean-up

Now that we have made the case for reducing the amount of CO₂ currently in, and being released to the atmosphere, what can we do about it?

5.1 Removing CO₂ from the atmosphere

Even though the greenhouse gases in the atmosphere are increasingly dangerous from a Climate Change perspective, a 400 ppmv CO₂ represents only 0.04% of the atmosphere - a minuscule amount to remove when compared to the 99.96% of other gases in the air. However, the problem essentially lies in the fact that this other 99.96% of the atmosphere will also have to be processed to get at the CO₂. Despite this daunting task processes termed Direct Air Capture (DAC) have been studied for some time. Absorption methods have been considered and prototypes built but no commercial plants are operating at this stage. They invariably use a chemical absorber such as sodium hydroxide (NaOH), calcium hydroxide (CaOH₂) or an organic substance that contains ammonia in one form or another. The sample of air is drawn over the absorber which is then heated to remove the CO₂. The CO₂ then can be sequestered, sold for Enhance Oil Recovery (EOR) or perhaps used as a raw material in methanol production.

If this technology could be made economical it would have immense potential as all sources of CO₂ could be targeted not just those from stationary emitters. Proponents such as Carbon Engineering www.carbonengineering.com and Global Thermostat www.globalthermostat.com certainly claim it could become so. However claims on the cost seem to vary from US$15 to US$600/tonne CO₂ depending on the source. Whether the lower figure includes the cost of the manufacturing the plant and consumables is not clear but if so this has to be one important tool for the job ahead - that is, if we can dispose of the CO₂ safely without more being produced or an unacceptable risk being created. The proponents of this solution suggest the required energy source could possibly be natural gas. The American Physical Society June 2011 calculate this would result in generating 4 litres of CO₂ for every 10 captured, meaning an extra 40% more CO₂ would need sequestering.

Why can’t we just decompose of CO₂ or convert it into a less harmful product? The answer is it can be done and it is being used in conjunction with methane to make methanol (CH₄O). The main issue with CO₂ is that it is a product of combustion of carbon, converting it back to carbon and oxygen takes energy and the laws of thermodynamics state it will take more energy than during its production – a no win situation. Even using catalysts and reactions with metal compounds takes energy in the form of heat. We currently don’t have enough carbon-free energy to spare for such an operation.

Mother Nature does a fine job of extracting CO₂ and converting it into sugars, cellulose and starches by photosynthesis in plants and trees but not anywhere near the rate we are currently emitting these gases. IPCC suggest perhaps the most practical method to extract CO₂ from the atmosphere is similar to the ancient art of making charcoal. That is, we can we can use so-called Bio-energy with Carbon Capture and Sequestration (BECCS), which involves growing various forms of vegetation on a large scale or using refuse from the timber and sugar cane industries to burn at a suitable power station with capture and sequestering of the resulting CO₂ underground.
A similar method is to char the vegetation (heated to high temperature in a reduced oxygen atmosphere) and adding it to landfill etc. or adding to soils to improve an area’s soil condition - Bio-energy with carbon storage (BECS). Most soil up to 1 metre deep already contains massive amounts (approx 2.2 trillion tonnes) of carbon naturally. One report suggests:

*The total soil carbon pools for the entire land area of the world, excluding litter layer and charcoal, amounts to 2157-2293 Pg of Carbon in the upper 100cm*’ On the surface BECS may sound much more attractive than BECCS. That is storage of a solid as opposed to a gas of much greater mobility and mass. There is debate however suggesting that this could lead to more global molecular oxygen depletion than that currently caused by burning fossil fuels.

5.2 Reducing the emissions from stationary emitters like fossil fired power stations

Carbon Capture and Sequestration (CCS) is regarded as crucial element in the suite of technologies available to offset total carbon emissions by the IPCC and they state that without successful CCS there will be a substantial increase in costs to bear to reduce atmospheric CO\textsubscript{2} emissions.

An Australian Government support paper states:

“Australia has abundant fossil fuel resources and CCS technologies have a potential to significantly reduce greenhouse gas emissions from the extraction, processing and use of these energy resources.”

One hopes this notion is not a suggestion that we can keep burning fossil fuels indefinitely as long as we can landfill the offending waste gas. As Saudi Arabia’s former oil minister Sheikh Zaki Yamani famously once said “The Stone Age did not end for lack of stone, and the Oil Age will end long before the world runs out of oil.”

Sequestration of Carbon Dioxide (CO\textsubscript{2}) is currently in use by some oil companies to assist with depleted flow of oil and gas and is also on trial by various government agencies to prove the concept for large scale disposal of the gas underground before it can enter the atmosphere. There is usually a real incentive for undertaking CCS, either by using the sequestering to extract more oil from depleted wells; to avoid a carbon tax; or receive a government subsidy.

![Global emissions 2014 by sector](image)

*Fig 5.1 Break-up of Global CO\textsubscript{2} emissions by sector as of 2014 Courtesy: World Resources Institute*
Capture of CO₂ from mobile emitters like vehicles, planes and ships is not really practical. Household emissions capture would also be prohibitively expensive, at least with present technology. So we are limited to reining in stationary emissions. Power stations, cement/lime plants, large manufacturing facilities are in the spotlight, accounting for say 50 to 60% of all emissions at the very best. CO₂ represents around 72% of all GHG emissions.

![Australian Carbon Dioxide emissions by sector 2013-14 (542.6 Million tonnes)](image_url)

**Fig 5.2 Break-up of Australian CO₂ eq emissions by sector as of 2013-14 Source: Dept. Environment**

*the make-up of the CO₂ eq was not stated*

Fugitive emissions greenhouse gases are designated as those escaping from coal, gas and oil exploration and flaring. Waste emissions are those associated with landfill, waste water treatment, waste incineration and biological treatment of solid waste. These presumably can only be partially captured by installing appropriate equipment. Assuming 50% of fugitive and waste gas could be captured in practice then the maximum portion Australia could hope to restrain from entering the atmosphere is even lower at 60%

In other facets of the fossil fuel world it seems impractical to think that while we continue to burn these fuels we can capture 100% of the CO₂ and somehow sequester it without massive development and investment in capturing it directly from the atmosphere. However we can hope to capture a majority of the emissions from stationary industry and electricity/heat facilities. So at best Australia could conceivably capture and store 60% or 327 million tonnes p.a. of its current emissions.

In today's world, the practicality of coal --- abundance, security, affordability--- has great persuasive power for governments faced with burgeoning energy needs and dependence on resources from distant, troubled regions.³⁴
5.3 So what is the status of CCS?

Enhanced Oil Recovery (EOR) CCS:

The research into CCS goes way back to 1975 when oil companies, mainly in the USA, began to use the CO₂ extracted along with natural gas (mainly methane) to 'scavenge' additional oil from depleting oil reservoirs - a process that was termed Enhanced Oil Recovery (EOR). Harvested natural gas often has anything between 5% and 30% CO₂ entrained when it is extracted. Consumers require the natural gas they use to have only a small percentage of CO₂ and certainly no more than 3%. So the excess is extracted and where possible pressurised and pumped into oil reservoirs that are reaching their end of life, in order to force out some of the remaining oil. Other companies, such as fertiliser manufacturers, offset manufacturing costs by selling their by-product CO₂ to oil companies for this purpose.

So far approximately 250 million tonnes of CO₂ have been sequestered worldwide in this EOR way. There is usually a monetary incentive for the company disposing the gas in this way so that the returns outweigh the costs. So often however there is more potential CO₂ contributed to the atmosphere from the recovered oil down the track than the CO₂ that was sequestered to gain it. The storage of CO₂ in relation to CO₂ from the extra oil retrieved can be as low at 0.01%.

There is a large Australian CCS project planned for Barrow Island near Dampier, off the WA coast, called Gorgon and is due to come on line around 2016. The natural gas extracted has up to 14% CO₂ which must be reduced to liquid natural gas (LNG) export quality. The operators of Gorgon, namely Chevron and partners including Shell and Exxon Mobil, plan to store 120 million tonnes of CO₂ in 2.3 km deep saline sandstone aquifers below Barrow Island which, according to one report, amounts to 40% of the project's total emissions. It will be one of the world's biggest CCS plants in operation, gradually ramping up to 7.5 million tonnes of sequestrated CO₂ per annum.

The CCS component of this project is budgeted at US$2 billion, of which the Australian Government has pledged the equivalent of US$54 million. The CCS project was approved in November 2008 when Australia still had a carbon tax to offset the CCS expense. Chevron's 2015 update suggests the CCS “work continues to progress rapidly”.

While Chevron have operated on the island for several decades now it has considerable environmental responsibilities, as the site is a Grade A listed environmental reserve requiring extensive quarantine procedures for all incoming transports.

Chevron and partners are liable for monitoring the site for up to 15 years after CSS operations cease (in some 40 years hence). After this time the WA and Federal governments have accepted responsibility for monitoring and management of the site on a 20% to 80% basis for …… who knows how long?

Non Power Plant Operations CCS:

Where there is no incentive through recovered oil to bury the CO₂ there is far less practical demonstration of this technology available, with approximately only 33 million tonnes having been buried globally to-date. Approximately 19 million tonnes, or over half of this total can be attributed to just two Norwegian natural gas enhancement projects (Sleiper and Snøhvit) that have an incentive of avoiding the Norwegian Government's Petroleum Industry carbon tax- currently set at
410 Norwegian Krone /tonne CO$_2$. This converts to AUD$63/tonne at time of writing. With the other six active projects, five are in North America and receive substantial financial assistance (like 67% to 100%) from their governments.

The remaining current non-power plant project is in Algeria, called Salah, which is a joint venture between BP, Sonatrach and Statoil, in which 1.2 million tonnes of CO$_2$ p.a. ex-natural gas refinement is being buried 14 km from the refining plant. The project has been suspended since 2011 after 3.8 million tonnes of the potential 17 million tonnes capacity of the saline formation had been sequestered due to “vertical gas leakage” concerns. There are very sophisticated monitoring facilities involved at this site, including seismic (earthquake) recording and satellite surveillance using a technology called Interferometric Synthetic Aperture Radar (InSAR) to monitor stresses in the cap rock and overburden as a result of the gas pressures used. The process is still under review. There is little published information on their cost but one estimate is around US$2.7 billion, which means if they do successfully bury the 17 million tonnes, even on a modest discount rate, this would have cost over US$200/tonne (nominal/current dollars).39

**Fossil fuel power station CCS:**

While there has been several pilot plants capturing a very small percentage of the CO$_2$ in flue gases in power stations in various countries but at the time of writing there is only one operational fossil fuelled power station to date that plans on capturing CO$_2$ on a large scale (>80%). This is Boundary Dam Unit 3 in Saskatchewan, Canada, an 110MW lignite fired station which was retrofitted with CCS equipment starting in 2014 to capture 95% or 1 million tonnes pa CO$_2$ at a capital cost of US$1.24 billion. It is scheduled for start-up late 2016. Originally owners (Saskpower) intended to retrofit a 300MW unit but due to escalating cost estimates the provincial government later decided on a smaller, less risk, project.40 There are other power station CCS project planned but not yet operational and ironically most would be targeting the EOR market.41

The CCS gear fitted to existing pulverised coal fired plants are estimated to consume something in the order of 24 to 42% more energy which ultimately adds to power costs, water demands and the extra CO$_2$ needed to be disposed. From the literature it could be deduced that Unit 3 would absorb an additional 27% more energy but Saskpower themselves say42 "Our facility anticipated to be 21%. However, other documents such as a report by CSIRO43 suggests this would be closer to 40% as per their Australian pilot trials. The plan at Boundary Dam is to pressurise the gas and pump it 66 km to a depleting oil well in Weyburn for the purpose of EOR. This presumably would offset costs but as the company owning the Weyburn site, Cenovus, states it has already used up all but 8 million tonnes of storage the balance over 30 years life may not bring in revenue for Saskpower. Weyburn's owners claim the sequestered CO$_2$ will increase their oil recovery by 17,000 barrels oil/day.

IPCC Report 2005 Chapter 8– Cost and economical potential44 indicates that for new pulverised coal power plants the cost is likely to lie between US$23 to US$35/tonne CO$_2$ captured but judging by the price tag of this retrofitted project it may be more than US$100/tonne minus of course any refund from EOR. The above mentioned CSIRO report indicates that for post combustion capture (PCC) in Australian the plants are likely to cost between A$62 to A$92/tonne of CO$_2$ without transport and sequestering, plus an additional operating cost somewhere between A$0.054 and A$0.063/kWh passed on to consumers (wholesale price increase).

There is a 582 MW Integrated Gasification Combined Cycle (IGCC) lignite fuelled plant called
Kemper\textsuperscript{45} in Mississippi, USA which is scheduled to come on line 2015. The notion of IGCC is that the coal is first 'gasified' with steam and air (or in some cases pure oxygen) to form a mixture of hydrogen, carbon monoxide (CO) and CO\textsubscript{2}. The latter is then removed from the stream, dried, pressurised and in this case will be used for EOR in that state. The remaining fuel gas (not dissimilar to the old ‘gas works’ town gas) is then burnt in a gas turbine to generate electricity. IGCC is considered more efficient regarding GHG emissions, especially if oxygen is used instead of air in segregating the CO\textsubscript{2}, as the resulting gas steam is far more concentrated in CO\textsubscript{2}, and therefore easier to extract. The CO will, of course, burn to CO\textsubscript{2}.

Kemper's budget has blown out from US$2.4 billion to US$5.6 billion from inception although a later report indicates it will be closer to US$6.1 billion. It plans to capture 65\% or 3.5 Mtpa of the generated CO\textsubscript{2} and transport it 96km to an EOR customer. The operator (Southern) has been granted US$700 million in federal grants and tax concessions and has been instructed to pass on US$2.8 billion to customers. It will be the first CCS and IGCC experiment in the USA and one of 2 out of an original 27 such proposals to have survived budget reviews. Whether it be US$5.6 billion, US$6.1 billion or even higher the electricity generation costs are likely to be substantially higher than the norm at US$0.07/kW. On just the capital cost depreciation alone it will costs in excess of US$90/tonne CO\textsubscript{2}.\textsuperscript{46}

Pilot plants:

There are 3 main CCS pilot projects currently operating. One in USA (Citronelle), one in Germany (Ketzin) and one in Australia (Otway). These efforts are basically designed to establish CCS strategies by the various governments, and are all under 0.1Mtpa capacity. Together they have successfully sequestered 0.43 million tonnes of CO\textsubscript{2} of which Otway has stored a total of 65,000 tonnes to-date and is now mainly in a monitoring phase. To put this in perspective Australia's Bayswater power station alone produced over 14 million tonnes CO\textsubscript{2} in 2012-13.

CO\textsubscript{2} turned to stone:

One true glimmer of hope for CCS, and one that would dramatically reduce the risk of CO\textsubscript{2} leakage over long periods has been generated in Iceland. A process named Carbfix\textsuperscript{ii} has been pioneered by a team of scientists experimenting with sequestrating CO\textsubscript{2} and H\textsubscript{2}S waste products from Iceland’s Hellisheidi geothermal power plants situated 25 km east of Reykjavic.

The notion is that to reduce the immense time scale for CO\textsubscript{2} to combine with various minerals such as calcium, magnesium and iron to form solid compounds there needs to be an increase of these minerals in the well strata. Typical saline aquifers, depleted oils and gas voids preferred for current CCS programs seldom apply, thus slowing down carbonisation to a snail pace. Alternatively basaltic rocks formed by solidified lava are relatively common in the earth’s crust and can be made up with as much as 25\% of such elements and hence are far more reactive with the villainous gas. Those basalt deposits with high permeability and hence surface area will provide more void space for the injected GHG.

\textsuperscript{ii} Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions – Juerg M Matter et al – Science AAAS sciemcemag.org 10th June 2016
Both CO\textsubscript{2} and H\textsubscript{2}S have been injected into the basalt bed rock at depths, between 400 and 800m, dissolved in water. The water is used as their vehicle and renders the gases far less buoyant making them less prone to migrate. Overall 175 tonnes of CO\textsubscript{2} and 128 tonnes of a mixture of CO\textsubscript{2} and H\textsubscript{2}S were injected over the experiment period.

The conventional methods of tracing movements of CO\textsubscript{2} in current CCS procedures would be ineffective with water dissolved gases so in this case the CO\textsubscript{2} was 'spiked' with radioactive carbon \textsuperscript{14}C to enable monitoring. Sulphur Hexafluoride SF\textsubscript{6} and also trifluoromethyl sulphur pentaflouride SF\textsubscript{5}CF\textsubscript{3} were also injected in minute concentrations to enable any plume migration progress to be monitored.

Eight monitoring stations where able monitor at depths between 400 and 1,300 m. Concentrations of pH, Carbon, SF\textsubscript{6} and SF\textsubscript{5}CF\textsubscript{3} were monitored over a 550 day period. The results were most encouraging with the calcification process advancing rapidly and achieving 95% completion within two years. Furthermore, as this process worked for a combination of gasses it may reduce the costly process of exhaust gas separation at other potential sites. However this may be true of mixtures of GHG's but it would possibly make sequestration of all power station flue gases impractical due to the huge volume of entrained nitrogen that must also be sequestered.

The report confirms substantial amounts of water are required (tests suggested as high as a ratio of 25.7:1 for CO\textsubscript{2} and possibly even higher for CO\textsubscript{2}+H\textsubscript{2}S storage but in an interview with the Guardian's Damian Carrington\textsuperscript{iii}, co-author Matters suggested seawater would suffice. Nonetheless transporting and processing these volumes of water, of whatever source would add substantially to the cost of sequestering billions of tonnes of CO\textsubscript{2} per year.

Also while used in small amounts we elaborate in Appendix 1, SF\textsubscript{6} itself is the most potent GHG eclipsing that of CO\textsubscript{2} over 22,000 times. Hopefully there would be another less potentially damaging catalyst that would suffice.

More detailed information on CCS is available in Appendix 5.

**Pros**

- CCS practises have been successfully carried out since 1975 and a total of approximately 290 million tonnes CO\textsubscript{2} have been sequestrated worldwide. There are no reported major leaks although further CCS at Salah has been postponed pending further monitoring with one well shut down due to a slight leakage. Hopefully we will have the same good track record when we target the 20 billion tonnes pa.

- If we are to tackle Climate Change head on it seems we may have to endorse CCS as a means of greatly reducing the costs later. In 2005 IPCC suggested there is suitable geological storage volume for at least 2000 Giga tonnes and possibly as much as 11000 Giga tonnes worldwide. Hopefully this does not imply to some that we have considerable time before positive action is adopted as energy facilities delay commitment to the necessary expenditure.

- Additional cost to the various stationary energy companies will be considerable once CCS is made mandatory and will likely expedite the closure of the less efficient plants for replacement with alternative less environmentally damaging units. The 2005 IPCC report

\textsuperscript{iii} CO\textsubscript{2} turned into stone in Iceland in climate change breakthrough – Damian Carrington – The Guardian, 9th June 2016
suggestions carbon capture alone from new pulverised coal power plants may cost between US$29 and US$51/tonne in CO₂. While that statement was made ten years ago the one example of retrofitting such plant (Boundary Dam) suggests a figure closer to US$100/tonne.

- Providing we can firmly establish competitive costs on direct air capture then this process is likely to be a considerable contribution in de-carbonising the atmosphere.

- Incentives for storing char in soils could also be of great assistance provided suitable research and monitoring insures we do not overload that sink to the extent that it later rejects the gas.

Cons

- Regulation frameworks for CCS are still in a state of flux and one can only guess as to how the various regulation from country to country will emerge.

- It is not clear as to who will continue the long-term monitoring of the sequestered CO₂ and possibly long after the initiating operator is no longer 'available'. Will this be another public funded operation? CO₂ stays in the atmosphere at least 100 years and in some cases thousands of years.

- What will the procedure be in the event of a major leak due say to an earthquake? The IEA suggests the 'the only best practice examples for such measures are those adopted from oilfield practise'. Does Deepwater Horizon spring to mind?

- Exactly who will be responsible for monitoring worldwide? Will it be an arm of the International Energy Agency (IEA) currently with 26 country members to be expanded to take in all other relevant states? The International Atomic Agency (IAEA) has more than enough problems tracking unregistered nuclear facilities with its 162 current member states including India, Pakistan, Israel and up until 1994, North Korea, all of whom are reported to have developed nuclear weapons.

- What happens if future generations want to search for bore water or geothermal heat sources? Will they have a 'Dial before you dig' number to call?

- Nature sometimes suffers gas attacks. There has been at least one massive natural release of CO₂ resulting in the deaths of 1700 people at Lake Nyos in Cameroon in 1986 caused by volcanic action.

- Duke University in the USA advise that if excess CO₂ becomes entrained in ground water it can change the acidity and the uptake of minerals. In particular, they found concentrations of iron, cadmium and zinc, among other minerals, increased by more than 1,000 percent after exposure to carbon dioxide.

- While not a mass escape of CO₂ something far more onerous gas leak from an underground storage facility has happened recently in California. On October 23, 2015, Southern California Gas Company (SoCalGas) detected a major leak at Aliso Canyon underground gas storage facility about 30kms from Los Angeles. In November 2015 methane was
escaping at the rate of 58 tonnes/hour although this slowed to 20 tonnes/hour by January 2015. Stopping the leak has presented a major challenge for the company and as of January 2016 an estimated 5 Bcft (101,000 tonnes) of the GHG had escaped. 51 In April 2016 SoCalGas announced they had found yet a new leak in the area. 52

- This CCS notion in itself highlights the seriousness of our plight. Using mother earth as a giant high pressure landfill for centuries hardly sounds 'World's Best Practise'. But we are running out of options as at the beginning of 2015 we are already 70% towards the 450 ppmv criteria where we are meant to be at by the end of the century. (i.e. (400÷450 = 70%)

- Not only will we be sequestering the emissions we normally have to deal with in regard to fossil power plants, to achieve this we need to generate more electricity and hence sequester another 40% CO₂ as a result. At best we are only likely to capture 95% of the CO₂ emitted as at least some will escape round up. Also, even with the Australian Carbon Tax (while it existed up until July 2014) at A$24.15/tonne CO₂ would hardly have deterred emitters if it was going to cost from A$62 to A$92 or more per tonne to just capture and say another A$10/tonne or so to transport and sequester, unless it of course it could be used for EOR, or that CCS be made mandatory.

- Possibly the most secure way to sequester CO₂ is to have it react with minerals to form a stable solid compound such as calcites and siderites. However these reactions evolve over considerable time, maybe thousands of years, which is time we just don’t have left.

- Regardless of the exact amount, this extra cost CCS (presumably to be covered by the tax payer and/or end-user) will bring the cost of fossil fuel electricity more in line with other generating options.
“We choose to go to the moon this decade and do the other things, not because they are easy but because they are hard.” John F Kennedy 1962

6. The Task at Hand

6.1 Pledges and spin

It must be of utmost importance that we act carefully, rationally and systematically to meet the sizeable challenge we all face. We simply do not have the benefit of unlimited time to procrastinate in the hope that someone will find a silver bullet. Each large project such as a power plant takes around 10 years or more from planning stage to operation, and that is a fair portion of the time we have left to significantly de-carbonise our economies.

Commitments thus far made by various governments to address Climate Change have, at best, been token in nature. The pledges made by 91 countries after the Cancun Climate Conference in 2010 would barely 'scratch the surface' of our task. In IPCC's own words, “If fully implemented, the pledges might reduce emissions in 2020 about one-tenth below the emissions level that would have existed otherwise - not quite enough to return emissions to 2005 levels.”

The latest declaration by our seven G7 countries 8th June included a statement which talks of “striving for transformation of the energy sectors by 2050”. If only we had that long!

Ironically the host country for this 2015 G7 conference was at the Bavarian hotel resort of Schloss Elmau in Germany. Although the Fukushima incident has been blamed by some for their decision, Germany passed a law back in 2002 to shut down all of Germany's nuclear energy capability by 2022 and replace them mainly with coal fired stations. By the end of 2015 they will have commissioned nine new coal plants with an installed capacity of 10.7 GW which will equal if not exceed their combined solar and wind capacity. As a consequence Germany’s GHG emissions rose 5% there between 2011 and 2013. Thankfully their emissions are now on the way down again.

In Australia’s case the newly downsized Renewable Energy Target (RET) is a plan to ensure 33,000 GWh (or 33 billion kWh) of electricity is derived from renewable energy by 2020. In 2012-13 we already generated 29.4 billion kWh of energy from renewables, mainly from hydro, so there is not much of advancement there.

There was also an Australian Government commitment by 2020 to reduce GHG emissions by 5% based on year 2000 emissions. According to the UN Climate Change Secretariat Australia’s net emissions in 2000, including those due to land reform, amounted to 0.513 Gt CO₂eq, although the official Australian Government figure is higher at 0.559 Gt CO₂eq. But taking the higher figure, 95% of 0.559 or 0.531 Gt CO₂eq should be our emissions in 2020. Actually the Department of Energy predicts this will be more like 0.577 Gt CO₂eq for 2020 even after a better than anticipated reduction amounting to 0.078 Gt CO₂eq. Now selecting the Australian Bureau of Statistics' fastest growth scenario for Australian population trends, Australia should reach a population of around 26 million by 2020. In that case the per capita emissions will be just under 18 tonnes per Australian, per annum, and still one of the highest rates in the world. For this lack of progress Australia is spending AUD$2.55 billion of public funds.

Regarding pledges at the United Nations Conference on Climate Change in Paris 2015 Australia falls behind most developed countries in agreeing to only reduce greenhouse gas emissions by 26 to
28 per cent below 2005 levels by 2030. The Dept. of Energy figures show we emitted 0.609 GtCO2eq in 2005 - the second highest record in 24 years. With a 28% reduction on Australia's CO2eq emissions in 2030 would still be at around 0.438 Gt CO2eq pa. The opposition party promise to trump this by reducing emissions by 45% over the same period should they be elected 2nd July. But sadly this is still not enough as Australia will need to be close to 100% by 2030. That will still look to be more or less those currently emitted by such as Spain, which has twice Australia's population.

Clearly there needs to be a quantum shift in our politician’s climate strategies.

6.2 How much more can we safely emit?

As mentioned in Chapter 2 monitoring our way to the safe limit of 450 ppmv CO2eq as per IPCC's definition may be difficult due to the problem in measuring inclusions such as tropospheric ozone, cloud adjustment due to aerosols and changes in solar radiation. The long term greenhouse gases themselves are regularly monitored and stood at 481ppmv in 201461 62. But not so the other factors IPCC also include, as we will definitely need to monitor progress it seems more practical to adopt the IPCC's allowable emissions in GtCO2eq provided in their Summary for Policy Makers (page 27) which states: 63

“Limiting the warming caused by anthropogenic CO2 emissions alone with a probability of >33%, >50% and >66% to less than 2°C since period 1861-1880, will require CO2 emissions from all anthropogenic sources to stay between 0 and about 1570 GtC (5760 GtCO2), 0 and about 1210 GtC (4440 GtCO2), and 0 and about 1000 GtC (3670 GtCO2) since that period, respectively. These upper amounts are reduced to about 900 GtC (3300 GtCO2), 820 GtC (3010 Gt CO2), and 790 GtC (2900 GtCO2), respectively, when accounting for non-CO2 forcings as in RCP2.6. An amount of 515 (445 to 585) GtC (1890 [1630 to 2150] GtCO2, was already emitted by 2011.”

What does this tell us?:

Assuming we need to give ourselves the best chance of limiting the annual average global temperature increase to 2°C and minimise (or hopefully totally avoid) the need for CCS for reasons stated in Chapter 5, we need to adopt IPCC's Representative Concentration Pathway 2.6 (RCP2.6). This means we need to take steps to satisfy the second last sentence in IPCC's criteria of limiting ourselves to 2,900 Gt CO2 absolute total emissions since 1861-80 giving us what IPCC regard as a 'likely' (>66%) chance of limiting the global temperature increase to 2°C.

Subtracting the range of emissions IPCC estimate to have been emitted up to 2011 (i.e. a range of 1630 to 2150 Gt CO2), adding published emissions for 2012-4 then projecting current trends in annual emissions into the future, we can predict the dates when we will run out of carbon credit. The remaining budget for 2016 is somewhere between 590 and 1100 GtCO2 depending on the range of uncertainty in the emissions estimated to have been emitted up to 2011. This means that we will have totally used up our Carbon Budget somewhere between 2028 and 2036. A recent report by the Universities of Queensland and Griffith suggest 2030 will be the year we hit the 2°C ceiling.64 Other non-IPCC scenarios such as those of the Climate Tracker Initiative suggests we even less time.65 For information, our sums are provided in Appendix 6. Any feedback will be made welcome.
We should take caution in that these timelines do not take into account the additional GHG emissions produced from providing the replacement renewable or nuclear energy generators that are required. It is highly likely replacement energy sources will need to use a certain amount of fossil fuel derived energy to supply and install them as is current the case with much of the solar, wind turbine, geothermal and hydro facilities. Further CO$_2$ is also emitted in the vast majority of cement (to concrete) and iron (to steel) manufacturing processes – generally referred to as “embodied carbon”. Both products will play a substantial part of re-energising the globe. Added to this dilemma is the significant ‘climate adaptation’ efforts many countries are now undertaking to reduce the impacts of Climate Change on their population, which generally involve increasing the size and resilience of infrastructure to reduce the risks of failure from extreme events.

It therefore seems essential that we keep all non-fossil fuel options open so that we do not burn up large portions of this carbon credit on replacements that themselves have high overall life cycle assessment to GHG or poor net energy characteristics.

Further the Carbon Budget is a global target so somehow it needs to be distributed equitably based on each country's fossil decommissioning burden. It is argued that countries most responsible for the majority of the emissions since 1750 should shoulder most of the burden. Some countries will have large wind energy capacity close to centres of population, some with geothermal, solar, hydro etc. Others may not be so fortunate, especially those with large populations but only a few such resources.

**The constraints:**

The timeline to de-carbonise our energy entirely is somewhere between 2028 and 2036 if we are to avoid exceeding the $2^\circ$C average global temperature increase. To be on the safe side we should consider that to be 2028.

The remaining global Carbon Budget as of 2016 was somewhere between 590 and 1100 Gt CO$_2$. To be on the safe side maybe we should consider that to be 590.

We need to choose the replacement alternatives that have net energy as high as possible to minimise additional GHG emissions while maximising de-carbonisation firstly in order to meet the Carbon Budget, then secondly at minimum cost.

We need to minimise reliance on CCS for reasons stated in Chapter 5.

Thorough planning and modification of electrical power grids is required to minimise outages and optimise 24/7/365 supply such that we can fully utilise the variable renewable sources (solar, geothermal, tidal, wind etc.).

In summary we need:

- to limit GHG emissions to somewhere between 590 and 1100 GtCO$_2$ say at maximum half way 850 GtCO$_2$, before 2028 including the GHG emitted whilst supplying and constructing any alternative energy systems.

- to minimise our reliance on capture of CO$_2$ and subsequent burial due to cost and future risk
of massive leakage. Other than nature's photosynthesis, endeavouring to retrieve emitted CO\textsubscript{2} from the atmosphere will be immensely energy consuming, costly and with the same risks as above.

- to choose appropriate alternative energy systems that are available to specific countries with low life cycle GHG and energy impact. Cost may, on some occasions, need to be the last consideration if de-carbonising targets become difficult to achieve.

- stringent monitory disincentives on the use of carbon based fuels (Tax, Cap and Trade etc.), with recovered funds to be used exclusively for de-carbonisation.

- international legislation to facilitate enforcement and an International body with powers to enforce.

- international funding (monitored grants) and provision of technical know-how in order to assist poorer countries to comply.

- There has been some research into so called 'geoengineering' whereby maybe as a last resort to ineffectual or even failed global de-carbonisation we may artificially reflect sunlight back into space using aerosols, clouds of minute mirrors etc.\textsuperscript{66} Fears abound that some countries may introduce this without unilateral agreement. Needless to say the risks of such a project must be fully investigated well ahead of any such implication. Much like CCS would we be replacing one immense problem to be dealt with in the future, by yet another? A major risk would have to be the possibility of over correction plunging the globe into an ice age.

But first of all we need the policy makers of the globe's sovereign countries to wake up to the challenge and cooperate in bringing this all about.... NOW.

The right choices:

Computer modelling has shown that many countries, including Australia, can feasibly gain all electrical and heat energy requirements from renewable sources such as solar, wind, geothermal, biomass and hydro as suggested by several academics after processing thousands of computer model scenarios, most of which require a time span to 2050.\textsuperscript{67,68} However, regardless of how inclusive such computer models are of all factors and scenarios likely to be witnessed in the real world, they remain 'models'. Real world precedents of 100% renewable electricity supply are somewhat scarce and trusting that an electricity power supply system can readily embrace such conversion without thorough trials would seem unwise. Much consideration needs to be given to planning and operation of this new generation of plant and power grid strategies. Most current power generation systems with their surfeit of fossil fired units have built-in 'inertia' and standby 'spinning' reserve in the event of a sudden change in demand or loss of one or more generating units. These reserve units can be automatically, or sometimes manually ramped up or down to accommodate any change in supply or demand. Even if a 500MW or larger unit ‘trips out’ the rotating mass of the slowing turbine generator provides sufficient time for the supply deficit to be rectified one way or another. These large units are often used to provide so-called 'base load' at more or less full capacity while energy sources such as gas turbines or hydro plants, that can be quickly brought on line, are used to take care of any 'peak loads'. Hydro generation has been shown to work well as a ‘base load’ power source, provided there is constant water supply, and also as a
means of storing energy for future shortages through pumped storage schemes. Naturally there must be an adequate water supply for consumption so droughts can present a serious management problem for hydro generation.

In contrast the availability of energy from solar PV and wind turbines can fluctuate considerably in line with their energy sources. The newer wind turbines do have built-in inertia to some extent, as do the concentrated solar thermal (CSP) plants which may have a certain amount of stored energy by way of their hot generating fluid. It is worthy of note that in January 2005 Denmark lost 90% of its aggregate wind energy for 6 hours, while in 2011 Germany lost 30GW of its renewable capacity suddenly. Such intermittency has mostly been managed through maintaining sufficient conventional back-up generation although such a scheme can lead to large fluctuations in energy prices.

Geothermal plants and hydro can provide a near 100% capacity factor where and when available. Tidal power supply is reasonably predictable, although inherently cyclical based on the solar and lunar cycles. Solar and wind are less predictable and introduce significant intermittency to power grids. Access to a geographically diverse of generation options with rapid switching arrangements should enable generators to meet demand at the correct voltage, frequency. Interconnection between national grids and hedge financing options also provide avenues by which power generators can reduce their financial exposure to such uncertainties. Even with such options there will most likely be a significant need in the future for some form of mass energy storage, and many options abound including heat banks, batteries, flywheels, hydrogen from water electrolysis, capacitor banks, compressed air storage, fuel cells or just plain back-up like natural gas fired turbines. Bulk hydrogen storage can be a major safety risk. Compressed air and hydro outperform battery energy wise many times over.

This calls into play other considerations, such as providing a more sophisticated or ‘smart’ grid where electrical energy supply is a two way phenomena with input from domestic and business users having some say in the overall supply plus clever software that is able to select the least costly but reliable electricity supply mix for customers. Energy planning and regular forecasting will become more significant and an electrical energy system of far greater sophistication will be required than we currently have in Australia (and practically anywhere else in the world today).

Ideally it would seem practical that such countries as Australia begin to de-carbonise the smaller separable regions, such as Tasmania and/or the Northern Territory, before others to provide the all-important learning curve on their grid operations using increasing amounts of variable, renewable energy systems. Their power system operators could then rely on surplus hydro, tidal or geothermal sources as rapid backup akin to a spinning reserve, battery backup or pump storage to accommodate any short-term gaps in supply. Tasmania would then be able to export an increasing amount of its current hydroelectricity via the interconnecting Bass Straight (~500MW capacity) high voltage DC transmission line (BASSLINK), once repaired, to help replace coal powered generation on the mainland.

A concern must be that without adequate know-how and sufficiently developed backup and integrated technology, that there will be a temptation by operators to recommission a fossil fuel plant or two to provide spinning reserve if 24/7 renewable electricity supply services cannot be maintained for any reason.

So what would this mean for a state like Tasmania? Tasmania's total commercial electrical energy capacity from renewables in 2015 was approx. 2870 MW (2275 MW hydro and 311 MW wind)
although the Climate Council suggest it is more like 3077 MW\(^71\). When all dams are full there is enough hydro capacity to meet all Tasmania's electricity demand for the year. Unfortunately the water inflows into the hydro catchments has now been steadily decreasing for several decades.\(^72\) In times of drought and low water levels Tasmania needs to import electricity from the mainland, usually energy that is generated by Victoria's brown coal plants, as was the case in 2006 to 2008, 2012 plus 2015. The only period when significant net energy was exported from Tasmania was in 2013 & 2014 when the carbon tax was in vogue and Tasmanian spot prices were also favourable.

So while there is no need to replace such renewable energy plants, Tasmania could conceivably become an electrical energy exporter and power system operator training facility. A move that could have the added advantage of greatly enhancing their state budget, technical know-how and employment situation. To achieve this they would need to replace the Tamar Valley natural gas fired open-cycle plant with more wind, PV and solar thermal plants, with projected renewal capacity able to provide the 11.6 billion kWh of electricity that Tasmania used in 2013-14\(^73\).These would have to be dispersed geographically as much as possible to assist in balancing out the variability of these types of energy generators over the Tasmanian grid. The grid itself may need to be brought up to date with the latest Smart Grid technology and the BASSLINK concept itself would preferably be overhauled and expanded to handle more exported hydro electrical energy as it becomes available.

However, as noted above, time is of the essence and other regions, states and entities should follow their de-carbonation no more than a year later. If Tasmania's experience showed they needed to rely on substantial amounts of hydro power to keep the whole supply system stable then other entities would be wise to also install back up sources such as hydro, geothermal, or batteries and to even consider the nuclear base load option if other backup options are not freely available.

If we adopt the same ratio of solar and wind as suggested by Professor Diesendorf for all of Australia we find we need the following new capacity for Tasmania.\(^74\) The main issue is that the proportion of hydro power in Tasmania (86%) is already much greater than the professor's 6% so in effect we could finish up with a considerable surplus of hydro generated electricity capability. Not such a bad thing we suggest, and if the existing BASSLINK cable could be renovated and upgraded Tasmania could become a true electrical energy exporter.

<table>
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<th>Prof Diesendorf mix</th>
<th>Tas electricity 2013-4</th>
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Table 6.1: The required minimum new non hydro installations to meet Tasmania's current electricity demand based on Prof Diesendorf's suggested renewable mix for Australia.

The capacity factors for wind and hydro are as per actuals for 2013 in accordance with the Office of the Economic Regulator, Those for PV, CSP and Biomass GT are as per the US National Renewable Energy Laboratory's (NREL) harmonised data. Imports to Tasmania of 1.9 billion GWh pa were required via BASSLINK during the drought years 2006-7-8-9. Water inflows to Tasmania’s catchment areas are showing signs of decreasing however. Quoting from
Choosing replacement electrical energy also requires consideration not only of the GHG impact but also the proximity of the required resources to centres of population that also have the required land and water available. Fig. 6.1 illustrates such requirements for the alternative energy sources. By way of example the Gemsolar CSP in Spain has a 15 hour backup capability using molten salt storage. This potentially provides 24/7 base load energy providing that is, day by day irradiation is fairly consistent. However, to provide such consistent power this 19.9 MW CSP unit spreads over a total of 195 hectares (almost 2 square kilometres).

As shown in Fig 6.1 current CSP plants require considerable water supply for make up steam generation and its condensation in a conventional fossil or nuclear plant. They adopt what are referred to as the Rankine or sometimes Carnot steam cycles. As will be covered in Part 2 of this book Australia's CSIRO is building a prototype CSP plant in Newcastle NSW using a gas (hot air) turbine generator based on the Brayton Cycle that will use far less water and provide a higher efficiency (up to 50%). This concept could show great promise for Australia with its water constraints.

While wind turbine plants require a considerable land area as the turbines need to be spaced such that they do not interfere with each other’s wind, around five times the blade swing diameters in all directions. But their individual footprints are relatively small. Thus there can often be dual usage of the land with some form of farming practices available, PV arrays on the same land. Offshore wind farms can be less intrusive on real estate but do require more of a maintenance challenge. Also some
are known to cause problems for shipping, long-line and net fisherman.

Geothermal plants can in theory provide base load electricity plus spinning reserve, both of which would be of immense benefit in a non-fossil power supply complex, especially if there is also water available. Unfortunately for Australia some geothermal sources are 'dry' with little or no local water sources and are far from centres of population. Beneath the Great Artesian Basin lies another large source of geothermal 'hot rocks' as yet energy from the combination of each resource has not been assessed.

Natural gas produces far less GHG than coal or oil if burnt but there are still considerable emissions and can arguably only be an option as a transitional replacement fuel. The question of using biomass as a source of energy raises questions as to land use and GHG in harvesting and preparation, due mainly to the 'inefficient' nature of photosynthesis. Biomass (mainly bagasse as a sugar production waste) makes up 55% of the Australian renewable contribution.

Hydroelectric power plants are very efficient (around 90%) provide there is sufficient water and can easily be ramped up quickly in the event of loss of energy elsewhere in any system or to provide peak lopping services. Naturally water supply is vital and with Climate Change the areas that may currently have adequate rainfall may have sufficient water resources in the future. China is developing massive hydro plants on its major rivers but the era of giant Three Gorges Dam-type projects may be at an end in other parts of the world due to the Climate Change rainfall supply risks involved.

Australia is the driest inhabited continent, and likely to become drier in the southern states. It is therefore unlikely that we will see an increase in the 8,500MW hydro capacity we have at present. Having said that, options to secure more pumped storage using the flows available would greatly benefit the flexibility of a renewable energy electrical grid.

Tidal and river flow energy plants can be sound investments in areas where there is a rich source and again reasonably close to centres of population. Unfortunately for Australia the resources are mainly off the NW coasts so transmission to populated areas would be costly and extensive.

Unfortunately the water inflows into the hydro catchments has now been steadily decreasing for several decades.

**Transport options:**

The next biggest slice of primary energy usage is used in transport. The proportion of total primary energy used in transport varies around the world. In the USA this figure is 28% while in Australia it is approximately 20%. The very high energy capacity of petroleum based fuels ensures they provide a considerable challenge in themselves to replace. Biofuels come reasonably close energy wise but their manufacture, at present at least, consumes considerable amounts of energy, and as so, considerable GHG emissions to produce, neither of which we have much to spare.

Perhaps even more critical than the choice of primary energy for electricity generation in terms of transport fuel options are the energy they take to produce compared to that they actually provide and their GHG emission factors. Unfortunately while there is a considerable amount of literature available on these properties for various fuels there is also great disparity regarding results.
It may seem difficult to imagine large earthmoving machines, heavy road transport and aircraft using anything other than a biofuel in the decades to come due to the amount of power they require. It would therefore be prudent to closely examine the various techniques for the various biofuels as suggested in Chapter 8 and set up International Standards accordingly.

For general road transport, hybrid plug-in or all electric vehicles (EVs) would seem to be the most promising in terms of cost although much research still needs to be done on the batteries being used to improve their high energy demand during manufacture (Cradle to Gate factor).

There are also varying ecological problems with the type of lithium ion batteries that use nickel and cobalt in their electrodes which also require more energy to make than those using other materials e.g. LiMn$_2$O$_4$ (LMO).

Hydrogen is an alternative but will need electricity to generate it - with associated energy losses. Mass storage of hydrogen has inherent safety risks and perhaps small solar powered hydrogen generators at the service station outlets would be preferable to bulk transport of hydrogen.

Electrification of rail transport is likely to replace diesel. Rail line electrification needs to be given priority over replacing old diesel locos with new ones. Needless to say electrical generation services will need rapid expansion world-wide to take up the place of transport petroleum fuels.

Regarding large sea going vessels it is hard to imagine these using batteries, biofuels or such and nuclear reactors may be the only current solution. Many existing oil tankers will become redundant and some may be converted to other forms of freight but the type of propulsion may well need to change. Recent studies have shown that the GHG footprint of small boating vessels is at least as great as the aircraft industry.

It would appear if we can reduce primary energy demand one way or another then this will ease the stringent time schedule. However it can be shown that if we have to increase primary demand with its current high fossil fuel component, in order to supply and construct the alternatives then select reasonable high, net energy alternatives the task, we feel is achievable but more professional modelling along these lines would be most helpful in selecting the optimal alternative energy mix for respective policy makers to act upon.

**The Game Plan:**

Albeit easy to say and perhaps difficult to fully achieve but what seems to be needed is:

1. Creation of an international carbon body requiring countries to sign up and contribute funds (say the International Carbon Abatement Body ICAB)
2. Bringing into international law requirements regarding fossil fuel dependency/addiction.
3. Global standardisation (ISO) of life cycle GHG and energy payback procedures with an intensive build-up of such data.
4. Distribution of the global Carbon Budget as of 2016 to create individual country Carbon Budgets.
5. Requisition of the individual countries to put forward their plans within a set time scale to de-carbonise their economies to meet the RCP2.6's $2^\circ$C target and with minimal CCS. The plans must emphasise a schedule of events that will be required to finish within the time-scale and their respective Carbon Budget. Provide aid, modelling and technical assistance to
third world countries to achieve these goals

6. Pier review of individual plans by ICAB and submission of any necessary changes.
7. Stringent 6 monthly monitoring of progress by ICAB with warnings as to any shortfall
8. Impose penalties for repeated failures.
9. Introduce or expand user pays disincentives, carbon taxes, boundary (import carbon) taxes.

This will obviously be costly but the alternatives appear much more costly and dire. One suggestion might be to divert some of the United Nation’s biennium budget of US$5.4 billion to this rather essential cause. Other options are discussed below in chapter 13.
“at every level the greatest obstacle to transforming the world is that we lack the clarity and imagination to conceive that it could be different” Robert Unger

7. Conclusions (Part 1)

Although the world faces a formidable challenge in order to preserve some of mankind's climate comforts and this challenge must be solved within very tight constraints, we still do have time. But we need to act now.

Meeting the targets outlined above will not return us to climate conditions of pre-industrial times. This will take a millennia even if we succeed, but it will give us a greater than two-thirds chance of limiting global average increase to 2°C.

Commitments by various government leaders to-date will be largely ineffective in meeting this challenge.

Public focus on the topic ebbs and flows with side issues like the Global Financial Crisis, severe terrorist threats and political expediency, being given priority. These may all need attention but not to the extent of the issue that threatens global stability. Employment, GDP and growth potential will all be greatly enhanced if we take this positive climate action. If not these terms will eventually count for very little.

Democratic governments are selected by voters. Those too young to vote do have freedom of speech. Autocratic governments are sometimes influenced by the voice of their people. Regardless of our perceived status we all have a say in state and world affairs. The catalyst for action to start on truly tackling Climate Change is in our (the general public's) hands.

Those people who still cannot see this escalating threat, or those that do but think it is a natural phenomenon, most probably will not change their stance in time to take positive action for one reason or another.

Those who do see a threat but feel helpless should consider their voting options, any unnecessary consumption of practically all non-essential manufactured goods and energy, maximising recycling, offsetting of personal carbon usage, divestment out of any fossil fuel assets and join one or more of the many Climate Change groups etc.

We will need all non-GHG emitting energy sources in varying degrees in order to de-carbonise our economies. This includes nuclear fission in the more populated regions, however unsavoury this option may appear too many after graphic images of the Fukushima tragedy. The hazards threatened by nuclear fission are minuscule in comparison to delaying action. These technologies may be replaced by the far lower risk fusion reactors whenever they become available commercially. But we have not the time available to wait for commercially viable fusion energy.

Large fossil fuel companies are predicting massive increases in sales in future decades. Why would they tell stakeholders otherwise and risk triggering a share price crash? And while we continue to demand their products to feed our various lifestyles, they will feel obliged to supply.

More rigorous and standardised calculations of overall emissions and energy demands are required of all alternatives to fossil fuel to better inform our choices of replacement energy systems.
Carbon capture and storage from fossil fuel power stations (CCS), carbon dioxide removal (CDR) from the atmosphere and albedo modification of our atmosphere (geo-engineering), can and should be avoided due to the risks, energy requirements as well as costs involved. This can be achieved if we begin positive action NOW. Commercial enterprises will abound to offer services such nonetheless.

Forestry and land use changes need to be rigorously monitored worldwide by the United Nations. Inducements to poorer nations to encourage sustainable land management must be put in place. Given the poor land use practices of the developed countries, monetary compensation to aid in such endeavours seems only fair.

Rigorous monitoring of all new nuclear installations, wherever they may be located, must be undertaken to ensure quality control, security, safety and world's best practice by the International Atomic Energy Agency (IAEA). Nuclear accidents to date may finally be responsible for around 4,400 deaths but this will almost certainly be minuscule in relation to the human casualties of unchecked Climate Change. Recent studies have suggested that the adverse health effects from small particulates emitted by coal-fired power stations make such technologies more dangerous that nuclear fission. See Appendix 11 for safety and waste comparisons. Tried and true concepts should be chosen as we do not have the time for novel concepts.

Fig. 7.1 - One forecast of global primary energy to 2035 – Courtesy: BP Energy Outlook 2035
While BP make the comment in their report that much depends on Climate Change policies it is clear we simply cannot afford to follow the above scenario. Even though it predicts continuation of the current slow-down in coal demand, the demand for oil and gas are considered to grow. Use of these three sources need to be zero long before 2035.

The immense satisfaction to be felt following a united effort by the world to truly step up to the challenge and win, can only be imagined. But few other human endeavours to date will come close in positive impact on this precious planet.
Part 2: Alternatives available to meet our energy challenge

“...catastrophic impacts of Climate Change will be felt beyond the traditional horizons of most actors – imposing a cost on future generations that the current generation has no incentive to fix”

Mark Carney - Governor Bank of England

8. The Energy balance, GHG deficits and unit costs

In view of the ever shrinking Carbon Budget that the globe's inhabitants have somehow to share out it equitably, seems apparent that, not only the financial aspects of any alternative energy strategy needs to be taken into account but also the GHG they are likely to emit over their entire lifetime and their net energy return. While fossil fuels have generated the vast amount of extra GHGs in our atmosphere, they have, up until fairly recently, provided a very good return on energy investment. In other words they have provided far more energy (like 100:1) than it took to extract them from the earth. On the other hand most alternatives are much less endowed. So by a nation choosing these in large quantities as a de-carbonising strategy may diminish that country's specific share of Carbon Budget quite dramatically, thereby reducing their capacity to de-carbonise entirely. Not only that, it is argued that there is a minimum value of such a net return on energy that will sustain a workable GDP.

Professor Charles Hall of the Suni college of Environmental Science and Forestry in Syracuse USA developed the concept of energy return on investment (EROI). Initially developed in the field of ecology, EROI simply means:

\[
\text{EROI} = \frac{\text{Energy returned}}{\text{Energy expended}}
\]

Put simply, what is the relationship to the energy we will receive from a chosen source compared with what energy it took to create.

Closely linked to the net energy argument and due to the fact that currently global primary energy is largely based on fossil fuels, is the overall GHG count of any de-carbonising strategy.

Life Cycle Assessment (LCA) is a technique to assess environmental impacts associated with all the stages of a product's life from cradle to grave i.e. from raw material extraction through materials processing, manufacturing, distribution, use, repairs and maintenance, and disposal or recycling.

This process also has the benefit of being able to assess the GHG of manufactured components that do not have an initial energy quota, such as batteries.

Last but perhaps not least is the financial impact of the chosen de-carbonising strategy. The most practical method of addressing this is the so called levelized cost of electricity (LCOE) or sometimes net energy ratio (NER) and represents the kilowatt-hour cost of building and operating a power generation plant over an assumed financial life and duty cycle. It is also used to represent the levelized cost of any form of energy, e.g. heat

Argonne National Laboratory in Illinois US operates for the US Dept of Energy. As well as publishing considerable material on LCA is also provides a free on-line spreadsheet to allow students, academics and the public in general to assist in calculating LCA of practically any manufactured item, fuel, metals and so on. It is called GREET and is available at https://greet.es.anl.gov/
Biofuel sources are no exception. Unlike solar wind hydro power plants etc., which have an operational lifespan in which to recover the energy or emissions expended on capital, operating and maintenance (like paying back a loan with interest), biofuels do not have that luxury. The energy and GHG expended on producing them over the entire life cycle, which is most likely to be fossil energy, must be exceeded by their usefully recoverable energy (i.e. the Lower Calorific Value or LCV).

As previously mentioned, conventional oil was once said to have an EROI of 100 i.e. 100 times more energy on being burnt compared to that expended on exploration, drilling, refining etc., as the sources of conventional oil dry up it's EROI is now only around 20. The same applies to natural gas. Shale oil and tar sand oil are much more energy intensive to produce and are claimed to have an EROI of less than 7 and 2.5 respectively and really only financially viable when the oil price exceeds US$85 per barrel. 75

Similarly biofuels such as bio petrol, bio diesel and ethanol are claimed to have scarcely any net energy return but there is currently a wide disparity in the literature depending on the adopted ground rules.

Published EROI values for corn-based ethanol for instance vary between 0.7776 and 1.7377 i.e. could either present a net loss or net energy gain. Again in studies reviewing EROI of ethanol from the North American switchgrass (panicum virgatum) vary from a low 0.7278 to 17.879. Similarly there are large differences in EROI estimates for biodiesel. Obviously the lower the EROI the more energy is needed to manufacture the energy generation unit the more GHG will need to be emitted. These differences appear to arise in the choice and interpretation of ground rules for which the US National Renewable Energy Laboratory (NREL) adopt what they term as a 'harmonising' strategy in an attempt to compare various reports on the same basis.

By way of example the EROI of a light emitting diode (LED) light bulb in 2008 was considered to be somewhere in the region of 12 to 24 but was on the increase due to improved technology and heading for 6580.

In view of the fact we have a diminishing Carbon Budget these two parameters (EROI and LCA) it seems imperative that they be regarded equally, if not more so than a product's financial and economic factors. In short we ask, what would be the point in spending trillions of dollars on the most financially favourable fossil fuel replacement equipment if we exceed the Carbon Budget in the process?
## Table 8.1 Some US published EROI/LCA/LCOE assessment data of electricity generators

<table>
<thead>
<tr>
<th>Energy source &amp; &amp;</th>
<th>Average EROI (dimensionless)</th>
<th>Average LCA (g/kWh)</th>
<th>LCOE*** 2013 US$/MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>7.8</td>
<td>35.8</td>
<td>125.3</td>
</tr>
<tr>
<td>CSP (trough &amp; tower)</td>
<td>17.8 to 25.6</td>
<td>10.6 to 17.9</td>
<td>239.7</td>
</tr>
<tr>
<td>Wind (on and off shore)</td>
<td>35.3</td>
<td>9.0</td>
<td>73.6 to 196.9</td>
</tr>
<tr>
<td>Geothermal</td>
<td>13.1 to 87.0</td>
<td>6.1 to 103</td>
<td>47.8</td>
</tr>
<tr>
<td>Hydroelectricity</td>
<td>117.6</td>
<td>5.5</td>
<td>83.5</td>
</tr>
<tr>
<td>Biomass</td>
<td>16.0</td>
<td>46.0</td>
<td>60 to 290</td>
</tr>
<tr>
<td>Nuclear (LWR)</td>
<td>714.3 to 769.2</td>
<td>16.5 to 16.6</td>
<td>95.2</td>
</tr>
</tbody>
</table>

Compared to fossil fuel generators

<table>
<thead>
<tr>
<th></th>
<th>Average EROI (dimensionless)</th>
<th>Average LCA (g/kWh)</th>
<th>LCOE*** 2013 US$/MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGCC **</td>
<td>909.1</td>
<td>487.0</td>
<td>72.6</td>
</tr>
<tr>
<td>Coal</td>
<td>476.2</td>
<td>1,234.0</td>
<td>115.7</td>
</tr>
</tbody>
</table>

Ranges in EROI, LCA and LCOE reflect the various types within an energy group.

Sources:

- **Black** Argonne NL, Life-Cycle Analysis Results for Geothermal Systems in Comparison to Other Power Systems: Part II – Nov 2011

** Natural gas combined cycle
9. Renewables

The label renewable energy means that the energy source is not depleted in any measurable way. Solar, wind, hydro, biomass, wave and tidal energy all rely on the sun's virtually inexhaustible supply in one shape or another. Geothermal heat energy source is from the radioactive decay of the earth's core plus gravitational compression and is also likely to be available for billions of years to come. So in there use the supply of 'fuel' is virtually guaranteed for the foreseeable future although in the manufacture, construction and maintenance of such power plants and fuels, at least for the present some fossil fuel will be used and hence they do have some carbon footprint.

9.1 Solar energy plants

There is a variety of solar energy plants in use, under construction or on the drawing board. A large range of designs exist from the simple evacuated tube water heater to the photovoltaic cell and on to the solar thermal tower systems (of which there are several concepts of each).

The global average intensity of the solar energy that actually reaches the earth's surface (referred to as solar irradiation or insolation) perpendicular to the sun's rays is around 6 kWh/m² per day (i.e. a power density of 0.25 kW/m²) allowing for fluctuations over the whole 24 hour period. As mentioned previously the 2014 global demand for primary energy (all sources) was 150 trillion kWh. Therefore based on global land area alone (130 million square kilometres) in theory, at least we receive nearly 1900 times more solar energy than the total amount of primary energy we are demanding. But as with any conversion of energy there will be losses, so considering solar energy conversion to electricity, this apparent over abundance figure may reduce to around a factor between 350 and 700 but certainly still a very sizable margin.

An obvious problem with solar is how dispersed this form of energy is. So a key problem is the collection and transmission of this energy to where the main consumption (population areas) is located in the world. In general areas of the northern hemisphere where most folks live is far less blessed than other parts of the globe regarding solar irradiation. Fig 9.1 shows just how diverse the solar insolation is throughout the globe.

Fig 9.1 Highest solar irradiation is not always near the high centres of population.

Courtesy: Solargis

The highly populated areas of Europe, Canada and China are not so blessed in relation to solar potential as Africa,
Middle East and Australia.

<table>
<thead>
<tr>
<th>City</th>
<th>kWh/m²/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adelaide</td>
<td>4.92</td>
</tr>
<tr>
<td>Brisbane</td>
<td>5.33</td>
</tr>
<tr>
<td>Canberra</td>
<td>4.99</td>
</tr>
<tr>
<td>Darwin</td>
<td>5.92</td>
</tr>
<tr>
<td>Hobart</td>
<td>4.17</td>
</tr>
<tr>
<td>Melbourne</td>
<td>4.42</td>
</tr>
<tr>
<td>Sydney</td>
<td>4.78</td>
</tr>
<tr>
<td>Broome</td>
<td>8.08</td>
</tr>
<tr>
<td>Port Hedland</td>
<td>5.14</td>
</tr>
<tr>
<td>Omskow</td>
<td>8.17</td>
</tr>
</tbody>
</table>

Table 9.1 solar irradiation at various Australian centres of population plus some with the highest levels. Source courtesy of www.sealite.com.au

In comparison China's level of solar irradiation varies from 3.38 kWh/m²/day in the very north east to 4.37 in Hong Kong. Finland's major cities receive between just 1.82 to 2.71 kWh/m²/day. Despite the low insolation in Northern Europe, Germany so far as installed enough PV to produce 38,000 GWh pa worth to date or about 7.5% of demand.

![Global Horizontal Irradiation](https://via.placeholder.com/150)

Fig 9.2 Australia's solar irradiation distribution - Courtesy of Solargis

According to the Australian Federal Government’s Bureau of Resources and Economics each year Australia receives more than 10,000 times more sunlight than our total primary energy demand. Much of course is widely disbursed but even the sunlight falling within 25 kilometres of existing transmission lines amounts to 500 times more than we use.
One organisation Desertec Foundation has the vision of harnessing solar energy from the Sahara desert and distributing the electricity generated to surrounding countries as well as Europe via low resistance, high voltage DC transmission lines Fig 9.3

![Diagram showing Desertec Foundation's concept](image)

**Fig. 9.3:** A concept for harnessing renewable wind and solar energy form high yield source in northern Africa and transmitting the electricity to high population centres.

Courtesy: Desertec Foundation

There is a similar concept for Australia, harvesting the solar energy from the outback to feed Australian cities and South East Asia with electricity again by high voltage DC transmission lines [http://www.desertec-australia.org/](http://www.desertec-australia.org/)

**Types of solar plants:**

The two major plant types currently used for harvesting solar energy for electricity generation are those using photovoltaic (PV) cells and those based on the solar thermal concept. The underlying principle behind PV cells is to transfer sunlight directly into electricity whereas solar thermal plants first convert the solar energy to heat and then the heat to electricity via a turbine or in some designs what is referred to as a Stirling engine.

The most recent developments in both types concentrate the energy from a large area exposed to the sun onto a relatively small area. Concentrated photovoltaic (CPV) adopt what is called a multi-junction PV cell which is quite small in relation to the type you may have on your roof. A CPV cell receive concentrated solar radiation via lenses or concave mirrors prior to exposure to the PV cell thereby intensifying the insolation. In the case of solar thermal units (CSP) the solar radiation is concentrated by way of:

- sun tracking mirrors (Heliostats) onto a boiler usually mounted on a tower or
- from a series of parabolic trough mirrors into a water or oil pipe centred at their focus or
- a single parabolic conical dish with an energy transfer device at its focus.
The high temperature fluid is later used to drive a steam turbine. The two concepts CPV and CSP are sometimes combined to generate both heat and electricity. This development is only in the early stages but has the potential for very high operating efficiencies.

In order to provide energy for so called daily peak loads (periods in the day such as evening meal times or in some cases midday air conditioner use) and for night time electricity supply some CSP plants also have heat banks to store heat in less demanding periods of the day which can then be drawn on to supply the extra energy needed during peak times. CPV plants on the other hand do not provide extra heat and so are limited to providing additional electricity for some form of energy storage or incorporating some other form of back-up. For heat storage substances that remain in a liquid phase at generating temperatures with a high thermal capacity are used, substances such as molten salts (usually nitrates of potassium, calcium, lithium or sodium or a mixture of same). Also rocks, brickwork and concrete are sometimes used as heat storage banks. Such banks can potentially provide an extra 7 to 15 hours of electrical energy.

Fig. 9.4 Spain's 19.9MW Gemasolar CSP plant.
Courtesy Torresol Energy (Sener 60%/Masdar 40%)

Gemasolar is equipped with a molten salt heat storage facility using a 60% potassium nitrate and 40 % sodium nitrate mixture to provide it with up to 15 hour backup source of energy. To cater for this feature the maximum theoretical thermal capacity of the plant is 119MW. The turbine electrical output however is only 19.9MWe. There is also a natural gas fired backup system available if the heat storage runs out. Commencing operation in May 2011. Gemasolar claims to have a capacity factor (percentage of time operating per year) of 63.1%. Costing an initial €230 Million the plant has a site area of 195 hectares and 2650 mirrors (Heliostats) covering a total of nearly 305,000 m². (The plant set an operational record of 36 days of uninterrupted energy supply just two years after commissioning.)
Australia has embarked on the construction of a CSP plant at Forbes NSW called Jemalong with a thermal capacity of 6MW to support its electrical capacity of 1.1MWe. It will have 5 towers and 3,500 heliostats and an air cooled condenser. There will be 3 hours of 'high temperature fluid' backup heat storage. It is a prototype for suppliers Vast Solar targeting larger projects ahead. From anticipated electrical delivery of 2.2 million kWh pa the overall efficiency will be 1.1/6 = 18.3% and the capacity factor of around 2200/1.1/8760*100 = 22.8%

The overall efficiency of a CSP plant is limited by the steam or gas (air) turbine plant. The former has an efficiency around 35% and the latter, which uses the heated air to drive a turbine could conceivably reach 50% efficiency and does do without the need for a cooling water supply.

CSIRO are developing a 200MWe solar thermal plant in Newcastle NSW that will eventually incorporate an air turbine referred to as the Solar Brayton Cycle. This configuration has the possibility of reaching 50% efficiency and water usage would likely be confined to mirror cleaning. 

However the efficiencies of these plants are only achieved while the solar plants are operating (like any type of power station). One of the largest solar plant so far built is the Ivanpah CSP plant in the Mojave Desert in California on 3500 acres (The plant was opened in September 2014 at a cost of US$2.2 billion, has a capacity of 392MWe and is powered by 173,500 heliostats sharing their solar energy between 3 towers. The overall efficiency is stated to be 28.72% gross with a capacity factor of 31.4% (i.e. 2751 hours operation pa). At present there is no heat backup system fitted.
But it may be the last CSP built in the USA according to the Wall St Journal and MIT Review due to costs, bird deaths and a poor capacity factor of around 13%. \(^{86}^{87}\)

Fig. 9.6 parabolic dish CSP with Stirling engines at the focus

A similar design to this but replacing the Stirling engine by what is termed a Dense Array Converter which is air cooled to maintain efficiency, making the unit essentially another form of CPV.

Fig. 9.7 parabolic trough CSP with heating fluid pipes at the focal line.
Yet another method of concentration using convex lenses termed a Fresnel Concentrator over each small PV panel.

While the overall efficiency of the type of single-junction (silicon based) PV cells householders and factories install on rooftops is only about 15 to 20% with a theoretical maximum of 37.7% the latest multi-junction PV cells have reached 46% overall efficiency and are headed for 50%. These use more expensive elements like germanium and tin but the solar concentration aspect of lenses is used to focus solar radiation onto a smaller area of the germanium/tin substrates.

The largest solar plant of either type built at the time of writing is the Topaz flat panel PV plant at San Luis Obispo County, California. It is a 550MWe CPV using 9 million cadmium telluride flat panels occupying 25 square kilometres of the County. The owners MidAmerica Renewables completed construction in 2014 at a reported cost of US$2.4 billion and in 2015 it generated 1,301 GWh of electricity giving it a capacity factor of 27%.

**Pros**

- Apart from the fossil fuel energy used in their manufacture, transport, and installation and disposal or in any fossil fuel back up, there is no operating carbon footprint deficit.
- Inland energy security for countries with this resource
- There are no other harmful emissions such as particulates and heavy metals
- They are more or less silent in operation
- They are very adaptable to remote areas using a localised grid, natural gas or battery backup system
- While the capital costs may be high with some types this is compensated for by low
operating and maintenance costs.

- PV research is continuing at a rapid pace in improvements in efficiencies and prices.

- While large solar power plants, take up considerable land area compared with fossil fired units which require coal storage, ash storage and often cooling water dams, solar plants can effectively be sited virtually anywhere. Solar avoids the large transport and disposal infrastructure for fuel and water supply required by fossil plants

- Solar plants require very little in the way of water supply and in the case of CSP the Brayton cycle does not use feed water at all.

- As with all renewable industries all the all-important ‘green’ job opportunities abound. Solar is a growth industry employing 174,000 workers in the USA and 13,300 in Australia (already more than in coal.)

- To improve efficiency the can use 1 or 2 angles of tracking and incorporating new concepts of concentrated PV and CSP with Brayton air turbines.

- Desertec principles may be more suited to Australia rather than Europe due to security issues

Cons

- As with wind energy their generating availability varies from hour to hour, day to day. While plants may have heat storage of natural gas back-up they still do not represent true base load reliability as with fossil or nuclear plants which can cause considerable management complexity for some utilities. More heat storage backup to enable CSP units to export more constant electricity supply will come at a cost as indicated at Spain’s Gemasolar plant mentioned above.

- Grid flexibility and response time are crucial to an electrical system's overall stability. As more solar and wind systems are connected to a grid the more input variations can occur resulting the system sometimes disconnecting them in favour of more stable sources so as not to jeopardise supply stability. This results in wasted energy and lower overall system efficiency. Until the so called ‘Smart Grid’ facility is fully integrated into an existing electricity grid system, and markets are made/allowed to provide correct pricing signals to users then this is likely to remain the case.

- PV cell current to voltage curve drops the higher the temperature. They are best suited to regions of cool sunny climates such as Tasmania.

- Currently some single junction silicon based PV panels have a fairly high EROI. With some the energy recovery takes nearly a quarter of the unit's estimated lifespan. 89

- As well as their intermittent operation and low capacity factors their power density is also low compared to fossil or nuclear plants. With such as roof top solar the space taken up is largely attributed to the building itself. If however, we plan to adopt a similar PV system as
the 550 MWe Topaz (which generated 1301 GWh in 2015 on a 25 Km² site) to replace just one brown coal station – say 1,480 MWe Yallourn W which together with its mine currently occupies approximated 5 km² of Victoria and which generated 9,806 GWh in 2014, we would need 188 km² of Victorian real estate. Similarly with CSP plants the real estate issue is a concern unless we place them out in the desert (of which Victoria has very little) and transmit electricity by high voltage DC cables to the coastal demand areas. Of the various CSP plants the least space hungry type is the tower with an average of 3.2 acres per GWh capacity. So Yallourn’s 9,806 GWh replacement by tower CSP plant would require something in the order of 127 km². If we extrapolate Gemasolar technology itself with its possible 15 hour backup we would need 173 km². The total Victorian brown coal electrical generation in 2012-13 was around 46,100 GWh. To replace all that capacity with PV or CPS works out around 880 or 600 km² respectively. For comparison the City of Bendigo takes up 147 km². Just how much of this land cost is included in the various ‘grid parity’ claims is not clear in the literature. Extrapolating the capital costs on a ‘per GWh’ rating may also represent an investment hurdle for large solar plants.

- And is 15 hours backup quite adequate? What if there are several consecutive days of bad winter weather?

- Solar plants have capacity factors of anywhere between 14 and 30% compared to fossil power stations which regularly operate at 85 to 90%

- Seldom does peak solar energy coincide with peak electricity demand.

9.2 Wind energy

For the total world’s land coverage the wind energy resource is estimated to be around one million GW or one trillion kW according to the Federal Government’s Geosciences Australia. Their 2014 Australian Energy Resource Assessment divides this further to 80,000 GW or 80 billion kW being mainly on coastal and close off shore regions and at mid to higher latitudes. Even so this amount is considerable. While wind farm capacity factors can vary between 15 and 50% from site to site those in Germany averaged around 17.5% in 2012 and those within the USA have varied between 28.1 and 32.3% in recent years. So at an average capacity factor of just over 21% the 80 billion kW could conceivably meet the entire world’s current primary energy demand let alone its electrical demand.

Of course, as with solar, we would also need a world-wide transmission network to cater for the demand and supply situation in each region which isn’t very practical under present technology and political diversity. Nonetheless wind power is the world’s fastest growing renewable source of energy averaging over 27% growth between 2000 and 2010 and the IEA figures show the total world installations in 2013 was 318,105 MWe. China leads the world with 91,413 MWe followed by USA, 61,110, Germany 34,660, Spain 22,959 and India at 20,150 MWe.

In Australia we have installed 3,240 MWe in total with South Australia leading the charge at 1205 MW followed by Victoria with 939 MWe. The Fig 9.9 presents the wind resource and operating wind farms for Australia
Wind turbines can start generating at wind speeds 3 to 4.5 m/s but typically operate between 10 to 16 metres/second and the energy generated increases as the cube of the wind velocity. As noted in Fig 9.9 Australia's mean wind velocity is at the lower end of this spectrum. Nonetheless Australia has considerable reserves. Some turbines can handle higher and lower speeds but cost and efficiency are factors. When the wind reaches higher speeds than the particular wind turbine can safely handle automatic safeguards come into place such as feathering the blades to reduce the drag or stopping altogether. This so called cut-off or survival wind speed varies from one turbine type to another and between 40 and 72 m/s although the average is around 60 m/s The maximum theoretical wind energy that can be extracted (Betz limit) is 59.3% of kinetic energy of the wind but the latest wind turbines can at best reach up to 70 - 80% of this or around 41 to 47% of the total wind energy. But that is higher than the thermal efficiency of most fossil fuel and nuclear power stations. The problem of course is the primary (kinetic) energy of the wind varies considerably from day to day or even hour to hour, whereas the fossil fuels have relatively consistent calorific energies.

Due to these variations in wind speed the wind turbines must have some means of regulating the frequency and voltage of the generated electricity before introduction to the grid.
Small wind turbines are available for domestic use and can be combined with solar panels to provide more consistent delivery. Several suppliers can be found on the Internet.

Wind energy in Denmark provided 39% of their electricity demand in 2014 at 9.30 TWh (9.3 billion kWh) from a total of 4,855 installed MW consisting of over 6,000 turbines. That represents an overall wind turbine plant capacity factor of 21.9%. The Danish government is targeting 50% of electrical energy generation from wind turbines by 2020. Their intensive turbine manufacturing and generation industry employs 20,000.

Currently the largest wind turbine being manufactured anywhere is by a Denmark/Japan (Vestas/Mitsubishi) Joint Venture. It is the V164-8MW and has a capacity of 8MWe. Each of the three blades is 80 metres long and weighs 35 tonne. The hub and engine room (Nacelle) section at the top of the mast weights 390 tonne.

In Spain wind turbine capacity 22,959 MW at the end of 2013 and generating 54.75 TWh. (54.75 billion kWh). In three months starting December 2012 generation from wind farms exceeded all other forms of electricity generation in the country representing 20.9% of all electricity demand out performing nuclear at 20.8%. The combined wind farm capacity factor works out at 22.7%. Their intensive turbine manufacturing and generation industry also employs 20,000.

Wind energy in Germany provided 8.9% of their electricity demand in 2013 or. 53.4 TWh (53.4 billion kWh) of electrical energy from a total capacity of 34,663 MW from over 22,000 turbines. That represents an overall wind turbine plant capacity factor of 17.59%. Germany’s wind turbine industry employs 96,000.
USA wind generated electricity in the first 11 months of 2013 was 167.7 billion kWh from a total capacity of 61,108 MW providing about 3% of the total electricity demand. Thus the overall capacity factor is 31.3% although a separate report suggests it was 32.3%. USA too has its own manufacturing companies. In 2012 this US industry employed approximately 80,000 people.

China has 91,424 MW wind turbine capacity in 2013. The most recent figures indicate that the generation represents only 2% of their electricity demand but on world standards the amount is huge. Their overall capacity factor works out at only around 15.7% which is partly due to the remoteness of their main windy areas which are in the North and a long way from their major centres of population in the East plus about 20% is not yet connected to their grid system. China also has a massive turbine manufacturing industry although actual employment figures are not openly available.

The largest wind farm so far is the work in progress 8,000MWe farm in Jiunquan, Gansu province North West China and scheduled to grow to 20,000MWe and that would equal almost 36% of the entire current Australian capacity. China plans to increase its wind energy capacity to 100,000MWe by 2020 as part of their renewable energy policy.

**Health Concerns**

While considerable criticism of wind farms regarding health matters have prevailed the Australian Government’s NHMCR could find no evidence of human ill health due to wind farms. Their conclusion was that ‘There are no direct pathological effects from wind farms and that any potential impact on humans can be minimised by following existing planning guidelines. Further The University of Adelaide’s research in 2013 concluded ‘The evidence considered does not support the conclusion that wind turbines have direct adverse effects on human health, as the criteria for causation have not been fulfilled.’

The MIT in the USA has also come to the same conclusion.
Compared to the ill effects of other energy sources currently in vogue the wind farms appear virtually pristine. Birds of course do occasionally get killed if they fly too close to the moving blades. But then again the same happens with road and air traffic. Nonetheless we continue to review claims of ill health allegedly due to wind farms at great tax payer expense.

Pros

- Many of the pros attributed to solar apply to wind including small carbon footprint, no harmful emissions, high capital but low operation and maintenance costs.
- Wind like solar can provide inland energy security for countries with this resource.
- While some have argued they represent a health hazard to humans this has been disproved on numerous occasions.
- The overall land use is moderated by the fact that over 90% can be grazed etc. Private land owners often receive benefits while still having grazing access for livestock. Solar plants are sometimes located within the same site as wind farms.
- Wind energy is even faster growing industry than solar in terms of ‘green’ employment opportunities.
- The EROI and LCA data on wind turbines indicates they are considerably more favourable than solar PV or CSP.

Cons

- As with solar availability and current grid flexibility can be an issue.
- Much as with solar the capacity factors of wind turbines are generally quite low in comparison to the fossil fuelled units they will be replacing. Average capacity factor for wind energy in Australia is around 29% whereas those of fossil power stations are regularly between 85 and 90%
- The turbines are a threat to birds and bats
- Seldom does peak wind energy coincide with peak electricity demand
- Wind and solar electricity generation do not always work in unison. Despite the fact that Germany in 2014 had 36,000 MW of wind turbine capacity and 38,000 MW of solar capacity, their total combined power feed into the grid seldom exceeded 30,000 MW
- Unfortunately wind farm development does sometimes experience considerable resistance from the public and the Not in My Backyard (NIMBY) syndrome
- Land owners of suitable wind turbine characteristics may not always agree to participate
- Regardless of their capacity wind turbine spacing needs to be 5 to 10 times the swept diameter of their blades to avoid interference. So countries with wind resources may not always also have the necessary available space
- Maintenance, especially for off shore units, can be an issue
9.3 Hydro energy

Hydro energy is one of our oldest renewable energy sources. The Ancient Greeks and Persians were using hydro power some 2000 years ago (Fig. 9.12).

Fig. 9.12 the Shushtar hydraulic facility in Iran dates back to the 15th Century BC

An ancient masterpiece of Persian engineering is attributed to Darius the Great in 5th century BC. There are two diversion canals on the river Kārun one of which is still providing water to Shushtar City via tunnels. There are also ancient water wheels for grinding grain. The diverted water downstream provides irrigation to 40,000 hectares of farming and orchard lands.

Fig. 9.13 Hydro power – Potential Energy to electricity

River flows can also be harnessed to generate electricity via the water’s kinetic energy. At times of low energy demand
and good water reserves the hydro systems are an ideal source for storing energy by way of ‘Pumped storage’. Using this technique the water downstream can be pumped back up to the dam or other upper reservoir using excess water to be available for use at peak demand times. In some regions of the world solar plants have been built adjacent to hydro plants in order to store surplus energy during sunlight hours that is released to the hydro turbines when needed later.

Theoretically there are enough geographical sites in the world to generate 38,607 TWh pa (38.6 trillion kWh) just by hydro generation alone or about 26% of our current primary consumption and almost twice the world’s current electricity demand. But this is theoretical and much of the sites are unsuitable for one reason or another and the more realistic, economically feasible hydro resource is 8.7 trillion kWh. Based on the hydro capacity currently installed world-wide (1.025 million MWe in 2012) and the kWh generated there from (3.756 trillion kWh) there is still some 2.3 million MWe theoretically economically available, mainly located in the Americas, Africa and Asia.

The world’s largest hydroelectric station is the Three Gorges Dam in China. It has a total capacity of 22,500 MWe from 34 turbo-generators. It involved the flooding of 632 square kilometres of land. This enormous construction received considerable criticism for the number of people displaced and the possible environmental impacts.

Australia has 7,297.2 MWe of hydro installed which produced 18.3 billion kWh in 2012-13 or 7.3% of all Australia’s electricity production.

The Federal Government’s Bureau of Resources and Energy Economics states that ‘Hydro has limited potential for further development, with any future growth being determined by water availability. Australia’s technically feasible hydro potential is estimated to be around 216 petajoules a year’. 216 PJ is equivalent to just over 60 billion kWh or more than three times the current. One assumes the water availability must indeed be their basic concern as Australia becomes even drier.

The largest hydroelectric plant in Australia is part of the Snowy River Scheme. Tumut 3 has a capacity of 1,500 MWe but although the combined capacity of Murray 1 & 2 is much the same they outperform Tumut 3 over 2008 to 2012 in electrical generation by a factor of 1.9

Fig. 9.14 the Three Gorges Dam, China
Environmental Concerns

Dams present problems for the environment through their effect on migrating fish populations and ecosystem functions that have evolved based on more intermittent water cycles. A number of older dams have been removed, particularly on the west coast of USA where migration of salmons have been adversely affected, or renovated to be made more environmentally friendly. Modern dams generally provide fish ladders, and even fish lifts, for migrating fish and more recently environmental authorities in many developed countries have been required water releases purely for ecosystem health and function.

Pros

- Hydro power generation is a well understood and well proven technology
- Inland energy security for countries with this resource
- Provides a means by which water supply can be made more consistent and affordable, much in the same way that energy storage could make energy supply more consistent and affordable
- It is an ideal source for peak lopping i.e. source of electrical energy that can be brought into use quickly when there is a higher than average demand.
- It can and in some places is used in conjunction with wind or solar as back-up energy
- Low operating and maintenance costs (although stopping the Franklin Dam on the Gordon
River in Tasmania proved to be a significant issue in Bob Hawke’s 1982 election campaign).

- Usually good public acceptance
- Can provide popular recreational areas and fishing opportunities.

**Cons**

- Displacement of local populations during dam construction
- Possible reduction of agricultural lands
- Increase risk of local earthquakes
- Increase methane production in flooded valleys
- Impacts on aquatic life and migrating fish
- Possible cause of conflict regarding to water resources downstream which is especially true when the downstream flow is over state and sovereign borders.
- Build-up of silt behind the wall/weir.
- Very dependent on water (rainfall) in the catchment area. Climate Change may well rewrite rainfall data in current catchment areas prompting caution regarding financial risk on some new projects.
- Dams per se have been known to fail as has recently happened to the Bento Rodrigues tailings dam in Brazil. But in late 1959, after torrential rains filled the Malpasset concrete arch hydro dam in France to its maximum capacity, it failed and allowed 50 million m$^3$ of water to devastate the city of Frejus. The death toll amounted to 273 and caused another 7,000 to become homeless. A Russian hydro turbine exploded at Sayano- Shushenskaya hydroelectric dam in August 2009 releasing flood water and causing 75 deaths.

**9.4 Biomass energy**

Biomass can be defined as renewable organic materials, such as wood, agricultural crops or wastes, and municipal waste, especially when used as a source of fuel or energy. Biomass can be burnt directly for energy or processed into biofuels such as biodiesel, ethanol and methane.

The original energy source for both biomass and fossil fuels is the sun. So, one could question why burning biomass is considered renewable and burning fossil fuels is not? After all, fossil fuels are merely very old biomass and the remains of micro-organisms. It is true that both were created through harnessing the suns energy to form cellulose, sugars and starches by converting CO$_2$ from the atmosphere and releasing oxygen via photosynthesis. As such the CO$_2$ on combustion is released once more into the atmosphere when either are burnt or used as fuels. The reason why biomass is considered renewable is because fossil fuels were created hundreds of millions of years ago when there was far more CO$_2$ in the atmosphere than there is today (humans were not around at the time). In contrast, biomass grown today removes similar levels of CO$_2$ from the atmosphere when it grows as when it releases when it is burned. Thus, on balance there is no net CO$_2$ addition with biofuels to the atmosphere except any from the fossil fuel used in equipment to grow, harvest and process the biomass. Thus assuming it is replenished at the same rate it is used and the fossil fuel in its handling is not excessive it is regarded as a renewable source of energy. It is also one of the few methods suggested by IPCC when combined with CCS that could be used to reduce
atmospheric concentrations of CO₂.

Sources of biomass include:

- Forestry and timber industry waste
- Agriculture industry waste e.g. bagasse, straw, green waste
- Animal and human sewage
- Paper industry waste e.g. black liquor
- Grains, sugar cane and seeds used to make biofuels
- Algae. In huge quantities in the oceans.

Biomass currently provides about 11% of the world’s primary energy, and mainly in underdeveloped countries. Less than 5% of Australia’s primary energy is derived from biomass.

The contained energy of biomass products compared with some fossil fuels is shown in Table 9.2

<table>
<thead>
<tr>
<th>Fuel</th>
<th>LCV (kWh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPG</td>
<td>12.78</td>
</tr>
<tr>
<td>Petrol</td>
<td>12.22</td>
</tr>
<tr>
<td>Diesel</td>
<td>11.89</td>
</tr>
<tr>
<td>Oil</td>
<td>11.67</td>
</tr>
<tr>
<td>Natural gas</td>
<td>10.56</td>
</tr>
<tr>
<td>Bio diesel (from waste vegetable oil)</td>
<td>10.28</td>
</tr>
<tr>
<td>Bio diesel (from canola)</td>
<td>10.28</td>
</tr>
<tr>
<td>Bio ethanol (from sugar cane)</td>
<td>7.84</td>
</tr>
<tr>
<td>Bio ethanol (from wheat)</td>
<td>7.60</td>
</tr>
<tr>
<td>Bio ethanol (from sugar beet)</td>
<td>7.50</td>
</tr>
<tr>
<td>Coal</td>
<td>7.10</td>
</tr>
<tr>
<td>Wood chips (10% moisture)</td>
<td>4.72</td>
</tr>
<tr>
<td>Straw/grass (15% moisture)</td>
<td>4.03</td>
</tr>
<tr>
<td>Wood chips (25% moisture)</td>
<td>3.89</td>
</tr>
</tbody>
</table>

Table 9.2 showing the lower calorific value of biofuels compared to those of fossil fuel.

The energy in ethanol is only around 60% of that of petrol per unit weight and hence more is needed to provide the same travel distance. However ethanol improves the octane rating of the blend over that of straight petrol. Only 10% ethanol (E10) is permitted to be mixed in Australian petrol as there is an issue with reactions with plastics and non-ferrous metals for higher concentrations in run-of-the mill production vehicles otherwise petrol engines have to be modified. Nonetheless the nation at the forefront of ethanol fuel usage, Brazil, has since the 1980s only limited their petrol dilution with anhydrous (>0.6% water by mass) ethanol to between 20% and 25% and use it only in local and even luxury imported vehicles that have been modified accordingly. In the USA and Canada what are termed Flexi-fuel engines can use an up to 85% anhydrous ethanol/petrol blend (E85).

There is no such restriction with Biodiesel in diesel engine vehicles and can be used blended or undiluted with only 14% less performance over its fossil competitor although some rubber tubing may need replacing in older vehicles. Wood waste is used as a fuel in community heating plants especially in Scandinavian countries.
Methane production: from animal faeces:

Anaerobic digestion is a relatively simple method of converting animal waste to methane for heating and cooking plus liquid fertiliser and is widely used especially in Asia. Anaerobic digestion is a series of processes using micro-organisms to breakdown biodegradable materials in the absence of oxygen. This natural process can be found in swamps, lakes and ocean sediments which can generate methane and CO₂ naturally. It is also used to harness the methane on farms and properties with animals. Fig. 9.17 illustrated the anaerobic principle.
Making bioethanol (C₂H₅O):

Bioethanol can be obtained by treating plants containing starch and sugars such as wheat, corn, cassava, sugar cane and sugar beet. Currently one of the most efficient ways, in terms of yield per kg per hectare, cost, simplicity of manufacturing stages and greenhouse gas abatement compared to petrol is by using sugar cane as feedstock. If sugar prices are slumping as they have for the last four years it would make good commercial sense to use some of the sugar cane crop to make ethanol.

This may change if the (cellulosic) technology of breaking down cellulose and lignin found in other plants improves making various perennial grasses and poplar trees more viable. Switchgrass (Panicum virgatum) grows wild in the Midwest USA in poor soils and has the potential to provide over five times more than the energy than is needed to process it.

Sugar cane is however a subtropical plant and some cooler countries use alternate feedstock such as sugar beat, cassava and sweet corn (maize). The latter has however driven up food prices due to taking up existing food producing land.

Fig 9.18 showing flow chart for ethanol from sugar cane. A yeast (Saccharomyces cerevisiae) is used in chemical treatment.
Making biodiesel:

Biodiesel on the other hand is made from vegetable oils and tallow. The inventor of the diesel engine, Rudolf Diesel actually ran his prototype ‘Rational Heat Engine’ in 1893 on peanut oil. Waste vegetable oils from restaurants and fast food outlets can be recycled into biodiesel and the McDonald food chain is rapidly converting all its waste cooking oil into biodiesel for its vehicle fleet.

![Figure 9.19 showing the difference in formulae between diesel (top) and biodiesel (bottom).](image)

The blue section at the end of the otherwise fully hydrocarbon chain makes up the difference. This is termed an ester functional group. Vegetable oils are chemically known as esters. Their molecules are formed from a linked series if esters and such are very much larger than the biodiesel shown above. They tend to gel (sort of solidify) at low temperatures and thus are unsuitable as engine fuel in colder climates. The process of breaking these chains down is called transesterification. It incorporates the addition of methanol (CH₄O) and a catalyst such as sodium or potassium hydroxide (NaOH or KOH resp.) which causes the chains to break forming biodiesel and glycerol. There are other methods using acids and enzymes. The production is usually in batches but one continuous process uses ultrasound excitation. Any moisture has to be removed either before or after trans-esterification, which breaks the vegetable oil down into glycerine and biodiesel, which are then separated usually by a centrifuge.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Yield Litre/ha.pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro algae</td>
<td>97800</td>
</tr>
<tr>
<td>Palm oil</td>
<td>5366 to 7133</td>
</tr>
<tr>
<td>Coconut oil</td>
<td>3223</td>
</tr>
<tr>
<td>Jatropha</td>
<td>2268</td>
</tr>
<tr>
<td>Olive oil</td>
<td>1452</td>
</tr>
<tr>
<td>Castor oil</td>
<td>1370</td>
</tr>
<tr>
<td>Sunflower seed</td>
<td>1070</td>
</tr>
<tr>
<td>Canola (Rape seed)</td>
<td>974</td>
</tr>
<tr>
<td>Peanut oil</td>
<td>748</td>
</tr>
<tr>
<td>Soy bean</td>
<td>541 to 638</td>
</tr>
<tr>
<td>Sesame oil</td>
<td>470</td>
</tr>
<tr>
<td>Corn (Maize)</td>
<td>220</td>
</tr>
</tbody>
</table>

Table 9.3 Comparison of biodiesel feedstock yields

While some feedstock plantations, such as oil palm and coconut groves, have efficient yields, they often impose of food production activities. Also they are also not as efficient at soaking up solar energy for photosynthesis as algae which outperform its rivals 8 to 16 fold. The proliferation of sweet corn farming as biofuels feedstock, particularly in
the USA, has been criticised for forcing the plant’s food price up, making it an even less practical solution in view of the relative yield.

![Fig 9.20 showing a US algae plantation. Courtesy: Solix Biofuels](image)

Waste, sewage or even salt water can be used and non-agricultural land. The industry is very much a work in progress while the search continues for the best types of algae and the best processing practices. Built adjacent to sewage plants algae plantations could make good use of the large amounts of waste water available provided there is also adequate sunshine in the area. Published EROI and LCA figures seem scarce but one report suggests EROI varies between 0.38 and 1.08 while LCA varies between 166 and 176 g/kWh. The same report advises water demand varies between 74.9 and 139 t litres/kWh.

Biofuels are available in Australia [http://www.biofuelsassociation.com.au](http://www.biofuelsassociation.com.au) and some organisations that have a supply of feedstock making their own.

Some controversy surrounds the true value of biofuels and their EROI. The US Department of Agriculture in 2009 claimed Biodiesel made from soybeans had an EROI of an encouraging 4.6 and the Canadian Biofuel Association propose even more optimistic figures for Biodiesel. Such an EROI is nothing like that of conventional oil, but still respectable. But the claim is disputed by Professors Pimental and Patzek in their 2005 paper who suggest it can take 27% more energy to produce than can be recovered, or a dismal EROI of $1 \div 1.27 = 0.79$.

It is also argued that the EROI of a particular source of energy must achieve a certain level in order to retain adequate funds for 'non-essential' purchases which often drive growth and maintain a standard of living. This minimum EROI ratio stated to be around 3.1 at the well head but is sometimes quoted as more than twice this figure.

As there are more than 250 companies world-wide in the biofuels industry including BP, DuPont and Tate & Lyle; it can only be assumed that either they have done the energy as well as the financial sums or they are operating with heavy public subsidies.
Fig 9.21 various claims re EROI on fuels. Courtesy: Centre for Sustainable Systems – University of Michigan

<table>
<thead>
<tr>
<th>Energy Product</th>
<th>Feedstock</th>
<th>EROEI (J delivered/J consumed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline (LowS)</td>
<td>Oil</td>
<td>3.54</td>
</tr>
<tr>
<td>Hwy diesel</td>
<td>Oil</td>
<td>3.5</td>
</tr>
<tr>
<td>LPG</td>
<td>NG</td>
<td>10.34</td>
</tr>
<tr>
<td>CNG</td>
<td>NG</td>
<td>6.91</td>
</tr>
<tr>
<td>Ethanol</td>
<td>Corn</td>
<td>1.63</td>
</tr>
<tr>
<td>Ethanol</td>
<td>Wood/Grass</td>
<td>0.57</td>
</tr>
<tr>
<td>Ethanol</td>
<td>Corn Stover</td>
<td>0.24</td>
</tr>
<tr>
<td>Ethanol</td>
<td>Wheat</td>
<td>1.24</td>
</tr>
<tr>
<td>Ethanol</td>
<td>Sugarcane</td>
<td>0.37</td>
</tr>
<tr>
<td>Ethanol</td>
<td>Sugar Beet</td>
<td>0.98</td>
</tr>
<tr>
<td>Butanol</td>
<td>Corn</td>
<td>0.29</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>Canola</td>
<td>9.69</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>Soy Bean</td>
<td>16.01</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Energy Product</th>
<th>Feedstock</th>
<th>EROEI (J delivered/J consumed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodiesel</td>
<td>Palm</td>
<td>6.37</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>Camelina</td>
<td>5.2</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>Algae</td>
<td>2.56</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>Tallow</td>
<td>1.95</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>Yellow Grease</td>
<td>8.9</td>
</tr>
<tr>
<td>HRD</td>
<td>Palm Oil</td>
<td>2.48</td>
</tr>
<tr>
<td>Methanol</td>
<td>NG</td>
<td>1.79</td>
</tr>
<tr>
<td>Methanol</td>
<td>Coal</td>
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</tr>
<tr>
<td>Methanol</td>
<td>Wood Res</td>
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</tr>
<tr>
<td>FT Diesel</td>
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<tr>
<td>BTL</td>
<td>Wood Res</td>
<td>0.77</td>
</tr>
<tr>
<td>FT Diesel</td>
<td>RDF</td>
<td>0.4</td>
</tr>
<tr>
<td>Gasoline</td>
<td>Wood Res</td>
<td>0.66</td>
</tr>
</tbody>
</table>
Table 9.4 Western Canada Biodiesel Association’s take on biofuel EROI

The plethora of conflicting data available on the Internet regarding the energy return on manufacturing even fossil fuels is somewhat disturbing even if we allow for a certain amount of industry’s ‘spin’.

**Pros**
- Greenhouse gas emissions will be considerably reduced by biofuels that do have higher EROI ratings especially if fossil fuels are used in their manufacture and distribution ratings. Some economists argue that the figure should be above 6 to avoid recession.
- Biofuels can provide inland energy security for countries with the available land resource
- Cellulose/lignin digestion technology looks promising
- Ethanol improves the octane rating of petroleum blends
- Biodiesel makes replacement of fossil liquid fuels very attractive as it does not need to be blended.
- Methane production on farm waste etc., provides a source of energy for poorer societies
- Wood waste can be used for district heating
- Bio-Jet fuels are already being produced to meet International standards

**Cons**
- Some biofuel emissions of the NOx range of greenhouse gases is slightly higher than petro-fuels.
- The EROI value whatever needs to justify the effort and the impact on food prices needs to be taken into account.
- Some biofuels are far less energy dense than their fossil alternatives.
- Opportunist feedstock production needs to be curbed dramatically where forest denigration or food supplies are being compromised.
- The amount of biofuels required to replace the current and growing use of petroleum based competitors will be a major, if not an impossible task, given resources available.

9.5 Tidal energy

Tidal energy arises due to the effects of gravitational force mainly from the moon and to a lesser extent the sun, which causes a 54 centimetre high twin ‘bulge’ of water moving across the surface of the oceans. In a period of 12 hours the earth rotates 180 degrees while the moon rotates only 6 degrees around the earth. Hence the bulge moves in relation to the body of the earth. This interacts with the continents and the topography of the ocean floor. The result is that most coastal cities experience a high tide every 12 hours 25 minutes. Although fairly rare some places on earth experience only one high tide per day while others experience four. When the bulge approaches a
shore its amplitude changes due to the decreasing depth of the sea bed below.

The sun modifies the height of the bulge depending on its location in relation to the earth moon axis. When the sun is totally in line with the earth and moon we get a so called a Spring tide (high-high) creating around 79 centimetre bulge and when at 90 degrees to this axis we get a Neap tide (low-low) which reduces the bulge to around 29 centimetres. These features complete their cycle every 29.5 days. (see Fig 9.22). When both sun and moon are at their closest and alignment at a new moon the theoretic bulge height is 93 centimetres. The bulge however is modified considerably locally by the sea bed topography and land masses.

The envisaged advantage of tidal energy is water’s very high density in relation to air and thus also to wind turbines (about 816 kg/m$^3$ at sea level and $15^\circ C$). Tides, while not offering continuous energy resource are very predictable making their harvesting seem more attractive.

In some areas of the seas and oceans wave power is considerably more concentrated than that of solar radiation. You may recall one of the highest solar energy is at Port Hedland at 6.14 kWh/m$^2$/day which relates to an average power density of $6.14\div24 = 0.256$ kW/m$^2$. In San Francisco Bay for instance the tidal power density is 3.2 kW/m$^2$ and it is fairly constant throughout the seasons.

![Fig 9.22 a simplified depiction of the tidal bulge caused by the gravitational pull of the moon and sun](image)

**Tidal barriers:**

The magnitude of this tidal change varies depending on the shape of the coastline and the amplitude is highest with wide mouth estuaries and is lowest at a long straight coastline. The highest tide is 16.65 metres between low and high tide at Burntcoat Head, Bay of Fundy, Nova Scotia, Canada. The lowest tides are around only15 centimetres.

The oldest concept of harvesting the potential energy of this phenomenon is to place a barrage across an estuary, a practice that dates back to the nineteenth century. The first such tidal power
station was the 240MWe Rance facility built between 1960 and 1966 that is still operational. It generates 540 million kWh pa on both the ebb and flow tides and has a reported capacity factor of 40%.

The South Korean Sihwa Lake tidal power station is the largest at 254MWe. It was completed in 2011 at a cost of US$355 million and generates 552.7 million kWh pa on the up flow tide.

Another project planned for Swansea Bay, Wales, UK uses a sea wall to enclose an 11.5 square kilometre lagoon is at Swansea Bay in Wales, UK. It will be a 240 MWe station and operate on both ebb and flow tides at a budgeted cost of £850 million.

By far the largest tidal project on the drawing board is the one extensively studied for the Bristol Channel Project (Severn Estuary) in the UK. Many proposals have been put forward from as early as 1925. The main attraction is the huge volume and velocity of sea water involved plus the maximum high to low tide head of 14 m. the second highest in the world. Numerous barrier sites with varying lengths have been studied up and down the estuary and the estimated costs for the latest range of proposals range from £10 billion to £34 billion and from 1000 MWe to 15,000 MWe at maximum capacity. The percentage of UK energy requirements it could supply are reported to range from 5% to 12% although the lower end of this range would seem more achievable based on the latest proposal. The lifespan (approx.120 years, is however considered to be considerably longer than most power stations which if correct would offset much of the higher capital expenditure. The latest proposal for 8.6 GWe producing an estimated 17 billion kWh pa gives a capacity factor of 22.6%

**Environmental concerns**

There several negative environmental and navigational concerns regarding the damming of estuaries. For this reason many offshore dams or sometimes referred to as 'impoundment' walls or tidal lagoons have been proposed where the containment dam is constructed from silt and rocks in locations where there are favourable conditions of tide and shallow water. Such construction materials are believed to have a much less invasive effect on aquatic life, shipping and wetlands. Load factors are stated to reach an incredible 48% and the use of multiple pools, if generation were staged would even improve on this figure.
Tidal stream generation (TSG):

A different concept entirely for harvesting tidal energy is to use turbines directly in the tidal stream area without using barriers or any type of containment. One such project known as the MeyGen project is about to start off with stage 1 (86 MWe capacity) development off the north coast of Scotland. When completed, the complex will have a capacity of 398 MWe. Stage 1 will be used as a proving exercise on turbine selection and layout. Cables from each generator will go to shore via horizontally bored tunnels.

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**Fig. 9.23 Potential tidal resources:** Courtesy: Renewable Energy Green Power
There are an estimated 11TWh of tidal current energy in the Pentland Firth. The MeyGen project is 85% owned by Atlantis Resources and ultimately will deliver a fully operational renewable energy plant of almost 400MW powered purely by the tide.

The blades are equipped with 180 deg pitch capability to allow them to reverse along with tidal flow. Some designs are completely emerged. A 300 kWe prototype has been installed in the Bristol Channel UK since 2003. Similar devices could be installed in ocean currents provided they were within practical distances from land for the transmission of energy generated.
Tidal Dynamic Power (DTP):

In 1997 Netherland Engineers Marcel Stive, Kees Hulsbergen and Rob Steijn came up with the notion of building a long 30 to 60 kilometre wall out to sea with a section at right angles at the end so the whole wall looks like a giant ‘T’ (Fig. 9.26). The coastal tides tend to run parallel with the coast in many areas and the concept of the wall was to hold back the tide on the upstream side of the T and use in-built turbines to harness the head of water flowing through to the other side. When the tide turns the water then flows in the other direction creating two generating periods twice a day. It is estimated just one such facility could have a capacity of 8,000 MWe and a capacity factor of 30%. Also there are many suitable sites and extreme high tide levels are not essential. So far there are no such power stations but China, with its massive coastal resource is getting very serious about DTP.

![Fig 9.26 showing the concept of a ‘T’ wall. Courtesy: Green Mechanic](image)

The rising tide water coming parallel to the shoreline is funnelled through turbines built into the cross wall to generate electricity. On the outgoing tide the situation is reversed.

There are estimated to be about 3,000 MW of tidal power resource along the coast around Broome, WA, Australia. High to low tide measures 10 metres. A study to install a 50MWe unit there some years ago was abandoned in favour of a natural gas power station. Overall the Australian continental shelf tidal energy resource is approximately 666.7 million kWh based mainly in WA, Qld & Northern Territory.

**Pros**

- Provides energy security for countries with this resource
- Low visual impact
- Anticipated long life of barriers, tidal walls etc.
- Tidal energy is considerably more concentrated in area than wind
- Little or no NIMBY issues, especially for offshore facilities
- The resources are usually close to high density populations
Cons

- Reported capital estimates range between $US1.36 to $US5.83 million per MW depending on the type and location. Average costs per kWh has been stated to be around US$0.24.
- Corrosion by sea water dictates the use of highly resistant materials
- Ebb tide only generation for barrage type facilities, as sometimes dictated by environmental grounds, puts the capacity factor on the low side and hence cost penalty per kWh
- The acoustic transmission of water is considerably higher than air when considering tidal turbine generation which may have detrimental effects on sea mammals which use their echo sounding senses for location.
- Sediment build-up and scouring of wetlands especially regarding tidal barriers did caused problems with France’s Rance project during the first 10 years of operation. Also fish shoals may be decimated if drawn through turbines.
- Shipping may need locks around tidal barriers requiring additional costs
- Although more predictable than solar or wind tidal energy is an intermittent resource and limited to around 10 to 12 hours per day and rarely at peak demand times.

9.6 Wave energy

Except in the case of tsunamis, wave power is a result of wind acting on surface water. Whilst in deep water away from any shore the intensity of wave power tends to be greater than those closer to shore which tend to become attenuated due to several factors. If however, shore waves are reflected by a cost line, sea wall etc., they tend to rebound and interact with the next incoming wave thereby virtually doubling their amplitude with no loss of energy (so called Clapotis phenomena). Breaking of a shore wave occurs when the depth of the water equals the wave height.

Wave power is measured as kW/m where the m represents a metre of wavefront e.g. a metre measured along the crest of a wave. Fig. 9.27 is an indication of this energy source available around the globe but these readings tend to vary considerably from season to season. In a northern hemisphere winter for instance, ocean waves are much more robust than those in the southern hemisphere (summer) and vice versa.
Wave power changes from location to location and season to season. As of February 2015 there are 176 companies developing wave energy harnessing devices.

Wave energy conversion is still very much in its infancy and there are many prototype harvesting devices being studied. They basically fall into four main types, namely overtopping, attenuators, point absorbers or oscillating water column units. They can all be used to extract energy near the shoreline or offshore.
Fig. 9.32 The Pelamis – an example of an attenuator. Courtesy: www.interestingengineering.com

The Pelamis is a 750 kW 150m long 700 tonne eel like device that captures wave energy in both pitch and yaw directions by pumping hydraulic fluid into a hydraulic motor/generator device situated at each 'hinge' node. Despite the potential of their technology the company went into administration in November 2014.

Fig. 9.33 A stylised representation of a one point absorber at the surface concept.
Western Australia has two CETO units (Ceto5 240kW) installed and connected to the grid at HMAS Stirling is a world’s first. A third unit will also be installed. The concept allows the units to be full submerged providing less hazard to shipping. Wave energy is converted to fluid pressure which gets pumped ashore and fed into a turbine generator for delivering electricity to the naval base and a small desalination plant. Importantly the device provides energy security to the naval base.

The Wells turbine, developed by Professor Arthur Wells, Queen’s University Belfast was specifically developed to operate regardless of the direction of the air flow (air in or air out) the turbine rotates in the one direction. It has symmetrically shaped airfoils as turbine blades with the axis of symmetry set at 90 degrees to the air flow such that the ‘lift’ is the same either way. However the drag coefficient is rather high and the best efficiency to date is around 15%.
Another unit has been built in Port Adelaide and scheduled for mooring in Port McDonnell. Yet another type of oceanic energy could be derived from temperature differences at different ocean depths referred to as Ocean Thermal Energy Conversion (OTEC) but it requires very specific site characteristics and is estimated to cost between US$2500 to US$15,000 per kW. Japan built a closed cycle 120kW OTEC plant on the island of Nauru commissioned in 1981.

Global wave energy resource have been estimated to be as high as 29,500 TWh pa (29,500,000,000,000 kWh pa) although the World Energy Council consider only 2,000 TWh pa commercially viable using current technology or about 1.8% of the total current global primary energy consumption. Australia’s reserves are mainly along the southern coastline of the mainland and Tasmania. Australia's wave resources are considered to be somewhere in the region of 9,6 TWh pa or 56% of Australia’s current primary energy consumption.

**Pros**

- Provides energy security for countries with this resource.
- Generally wave capturing devices operate silently
- Low visual impact
- They take up minimal land area
- Compared to solar and wind the energy source is fairly consistent albeit variable over seasons.
- Shore line erosion in the area concerned could be attenuated as the wave energy is decreased.

**Cons**

- Wave energy is still very much under development and some prototype designs are inefficient or suggest poor EROI
- Salt water corrosion has to be addressed.
- Navigation in the area concerned needs to be directed
Capital cost estimates ranged from US$6,000 to US$16,000 per kW in 2005 and US$0.36 per kWh

9.7 Geothermal energy

Besides the energy from our sun which is the primary source for solar, wind wave hydro and partial tidal energy there is another renewable primary source at our disposal; namely geothermal. The core of our earth is molten matter, the result of residual radioactive decay and gravitational collapse. The heat radiates out through the thick mantle and into the earth’s crust and can be witnessed at the surface in geysers, hot springs and volcanoes. Granite deposits closer to the surface are also often sources of heat due to their inherent radioactive decaying elements.

The estimated global resource is 100 PWh or 100 trillion kWh and is most concentrated along the edges of the tectonic plates.

This heat source is available for exploitation and the adoption of geothermal energy capturing sites is most observable in countries like Iceland, USA and New Zealand where the heat is easily accessible close to populated areas. Table 9.5 provides a list of operating plants.

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Table 9.5 A list of currently operating geothermal plants

The first geothermal plant was put into operation in Larderello, Italy 1904 as a demonstration by Prince Piero Ginori Conti. The dry steam field in this area still continues to produce geothermal energy.

The most common source of geothermal energy is so called Hot Dry Rock (HDR) named because it exists where there is little or no ground water in the region. The rock may need to be fractured to allow imported water to be pumped down and through the fractures before being extracted and used to drive turbines. Much of Australian resource is HDR and mainly located in areas of low
population (Fig 9.37).

So called hydrothermal resources do have some form of ground water sometimes providing steam directly but usually at a much lower temperature and pressure than conventional fossil fuel or nuclear power stations. Temperatures of the steam/water fluid extracted range between 100\(^\circ\) and 350\(^\circ\) C. The higher temperatures are used to generate electricity. Currently there is somewhere between 8,000 and 11,000 MW capacity world-wide. Extractions of lower temperature fluids (30\(^\circ\) to 150\(^\circ\) C) can be used for regional heating, laundries, swimming pools, industrial processing etc., and currently forms the majority of the world’s geothermal energy extraction.

**Environmental concerns**

Depending on the extent of any entrained contaminants (mainly Hydrogen Sulphide (H\(_2\)S), Ammonia (NH\(_3\)), Methane and CO\(_2\) plus metals like mercury and arsenic) contained in the extracted fluids so relevant environmental regulation may require the plants to have intermediate heat exchangers and a secondary circuit pipework to the end-user/turbine so the contaminated fluid can be pumped back underground, called binary units. New Zealand’s North Island recently commissioned the largest such plant at Ngatamariki Geothermal Power Station near Taupo. It has a capacity of 100MWe is currently the largest of its type.

Another form of geothermal heat extraction involves the use of heat pumps to extract the heat from the atmosphere much the same principle as reverse cycle air conditioners except allowing the extraction of heat from shallow resources. These and subsoil coils are becoming more common in northern European countries mainly for domestic heating (and cooling).

**PREDICTED TEMPERATURE AT 5KM DEPTH**

Source: Geoscience Australia 2010a.

Fig. 9.37 the main areas of Australian Hot Dry Rock deposits. Courtesy: Australian Institute of Energy
Interestingly much of the larger high temperature zone (red) lies below the Great Artesian Basin water supply.

![Diagram of a multi well geothermal plant](image)

**Fig 9.38**: A typical cross section of a multi well geothermal plant

![Image of The Geysers Geothermal Complex](image)

**Fig 9.39**: The largest geothermal plant as of 2013 is The Geysers Geothermal Complex in California where 18 units provide electricity and rated at 900 MWe. Courtesy: Power-Technology.com

Australia has just one geothermal power plant operating in Capricornia. It generates just 0.08MWe or about 25% of demand to the local Birdsville township with the balance being supplied by gas and diesel generators. The extracted water from the 1.28 km deep bore is only 98°C. As this temperature is insufficient to drive a conventional steam turbine it transfers the bore water heat to an organic compound iso-pentane liquid via a heat exchanger which flashes the liquid to a vapour which then drives an expander (effectively a gas turbine) and generator set.
Pros

- Provides energy security for countries with this resource
- Like most energy systems geothermal energy can be used to both heat and cool
- Relatively clean energy with little in the way of emissions
- Little or no noise pollution
- Base load capability – little energy fluctuation, >80% capacity factor.
- Steam/Hot water sources require little in the way of maintenance cost
- Much like wind farms there is considerable free land available at a site which can be used for grazing etc. Geothermal plants use only around 3.5 m²/kW which compares to that of coal fired plants.
- Competitive generating costs between AUD$0.10 & $0.30 /kWh depending on capacity.

Cons

- Considerably lower efficiency in regard to power generation than conventional fossil fuel and nuclear plants due to lower temperature. More cooling water is required for the condensers but most of this can be recycled.
- Resources not always close to potential users, grid systems and industry
- High upfront costs regarding exploration, drilling, fracturing etc.
- Water injection can precipitate seismic movement as it acts as a lubricant on already stressed rock strata.
“An advanced city is not a place where the poor move about in cars, rather it’s where even the rich use public transportation”

— Enrique Penalosa

10. Transport fuels

Transport fuels need particular attention because they are a major source of greenhouse gases (some 27% of world energy related emissions), and they are connected to people’s mobility, an extremely important aspect of our modern economies, our socio-economic well-being and connectivity. One major issue is suitable candidates for their replacement. Petroleum products have relatively high inherent energy and EROI, although the latter is decreasing steadily as the resource becomes less accessible. Alternate biofuels, while having moderate inherent energy characteristics, as stated they have a low EROI. Unless production techniques can somehow advance to overcome these shortfalls the biofuels are likely to become a heavy burden on the Carbon Budget and thus very expensive. Alternates to the ubiquitous internal combustion engine (ICE) will most likely predominate a future transport scene, as sad as that may seem to some. Alternate biofuels, while having moderate inherent energy characteristics, as stated, have low EROI.

10.1 Methanol, Ethanol and Biodiesel

These biofuels have been described in Chapter 9

Pros

- Fossil fuel free alternative transport fuels
- Liquid at normal temperatures hence high density
- Could provide political homeland security of supply

Cons

- Low EROI compared to conventional oil and coal
- Competition for arable lands and food resources

10.2 Aircraft fuels

We briefly covered aircraft fuels in Chapter 9. As the international and domestic air travel industry represents approximately 10% of current GHG emissions and anticipated to grow by 5.4% pa according to IATA.

There are basically two methods of making “renewable” or synthetic jet fuel that are currently in vogue. One is called synthetic paraffinic kerosene (SPK) and the other, hydrated renewable jet fuel (HRJ).

The SPK method first uses what is known as the Fischer- Tropsch Synthesis (FTS) process developed by German scientists Franz Fisher and Hans Tropsch in 1925. This process is used to convert a range of syngases to long chain hydrocarbons using carbon monoxide (CO), hydrogen and a catalyst such as iron oxide. These are then ‘cracked’ and separated to form various jet fuels labelled FT-SPK. Much of their properties are almost identical to conventional jet fuels and are usually used as a 50:50% blend with conventional jet fuel for both commercial and military aircraft. The feedstock syngas can be made from biomass as well as from coal and natural gas.
On 22nd September 2010 a South African airliner flew from Johannesburg to Cape Town on 100% FT-SPK fuel supplied by Sasoil Petroleum.

One disadvantage of FT-SPK is that it lacks what are known as ‘aromatic’ hydrocarbons which have the property of helping O-rings and other seals to swell thereby improving their performance. For this reason they are currently only used as part of a blend.

The feedstock for HRJ can be non-food oils from oil seeds and algae which are treated with hydrogen, removing any oxygen and contaminates. The long chain hydrocarbons are then cracked much the same as in the SPK process. HRJ fuels are also being developed to blend with conventional jet fuels. It is hard to imagine some of these are going to have a high EROI

In 2014 the US Naval Research Laboratory (NRL) began generating synthetic hydrocarbons from sea water by extracting CO$_2$ and hydrogen to form the long chain hydrocarbons using an iron based catalysts and then polymerising them to suitable fuels. Their predicted cost were proclaimed by some to be between US$3 and $6/US gallon (3.8 litres) which seems remarkably low compared to previous reports (up to US$150/gallon). Even at the 100 milligrams CO$_2$ per litre level of sea water it is obvious that a truly enormous amount of sea water is needed to extract enough to make up each litre of jet fuel so it will be a very energy intensive process. NRL’s website does not mention this but a ‘back of the envelope’ calculation suggests around 26 tonnes of sea water would have to be processed to create each litre of jet fuel. An F22 jet fighter for instance would use up somewhere in the region of 15,000 litres per hour when flying on afterburner.

**Pros**

- A potentially fossil free jet fuel alternative
- Military energy security

**Cons**

- Very low EROI and some claim this may even be negative

### 10.3 Hydrogen (combustion)

If our planet possessed massive free, molecular hydrogen deposits we would be much blessed energy wise. Presumably burning huge amounts of hydrogen to feed our insatiable energy appetites may cause more rain to fall but little else. Unfortunately there are no such deposits. While being the tenth most abundant element on earth, hydrogen is always combined with other elements such as with petroleum products and water. When we burn petroleum products there is an exothermic reaction, meaning heat is released. On the other hand, electrical energy, around 53.5 kWh/kg is required to extract hydrogen by breaking down water into its two constituent’s hydrogen and oxygen.

\[
2\text{H}_2\text{O} + \text{electrical energy} \rightarrow 2\text{H}_2 + \text{O}_2
\]

Otherwise we have to break down fossil natural gas. As Table 2.1 shows the most energy we could get back is 33.3 kWh/kg or 62% and that will reduce further when converted to electrical energy by the fuel cell. When we take into consideration the primary energy required to extract the hydrogen from water the EROI is even much less.

As such hydrogen, praised by pundits as being the new age fuel due to its non-toxic, virtually non-
polluting and plentiful nature is not really an energy source at all but an energy carrier much like electricity. As it competes, and very poorly, with electricity energy competitor, return on energy investment wise we would have to ask ‘why bother’? To quote Ulf Bossel\textsuperscript{101} “We have an energy problem not an energy carrier problem”. This argument is reinforced by the fact that the electricity infrastructure is largely in place globally so why introduce a competitor that would require the equivalent capital expenditure.

One exception may be to convert electrical energy to hydrogen extraction as overnight storage at a solar or wind energy plant. When the Aswan dam was built across the River Nile in Egypt in the 1950s it had an electrolysis and storage used for peak lopping. Nonetheless the process is energy hungry.

Currently a less energy extensive method to use is to beak-down natural gas using steam into hydrogen and $\text{CO}_2$ with losses of around 10\%. Again such a process uses a fossil fuel and must be discouraged.

$$\text{CH}_4 + 2\text{H}_2\text{O} + \text{Heat} \rightarrow 4\text{H}_2 + \text{CO}_2$$

There are other issues with hydrogen such as safety and containment. Being the smallest of atoms hydrogen has the tendency to work itself into and sometimes through containment vessel walls causing some metals to become brittle and companies are experimenting with materials that resist this problem. Also because of its low molecular weight the energy to compress hydrogen to suitable pressures is 8 times more than natural gas and 15 times more than that of air.

Metal hydrides are considered better storage vessels than regular fuel tanks although release of the hydrogen when needed is retarded. Again researchers are looking at ways of improving this property.

In Australia from 2004 to 2007 the Western Australian Government trialled three hydrogen fuel cell buses covering a total of 285,000 kilometres around Perth. While environmental considerations made these very attractive means of public transport the cost of the fuel was a major disadvantage and would only become competitive to say diesel without some form of carbon penalty (even when oil prices were US$120/barrel).

**Pros**

- Plentiful source in the form of fresh and sea water providing political security
- Clean GHG-free energy carrier
- Candidate for use as an energy storage media

**Cons**

- Not available in molecular form globally requiring energy to release it as such.
- Renewable energy needs to be used over natural gas reforming if GHGs are to be avoided.
- Cannot compete both in respect to energy and cost with its main competitor electricity.
- Major infrastructure is needed if adopted as a transportation fuel.
- Containment issues.
- Hydrogen fusion, as opposed to combustion, is likely to be a much different story. (Chapter 12)
10.4 Battery powered vehicles

Hybrid and electric vehicles have been with us for quite some time. Ferdinand Porche created the first so called hybrid vehicle in 1901. The first all-electric car goes back to the 1880 before the ICE was developed to the stage at which it became the favoured form of transport. The development of the rechargeable battery goes back even further.

The conventional hybrid vehicle converts the energy that would normally be transferred into heat while applying conventional brakes into chemical energy inside batteries which can later be used for propulsion when required. This is done by way of a generator/motor to charge purpose designed batteries. The fuel based motor characteristic of the unit takes over when the chemical energy thus stored in the battery is discharged to it in the form of direct current (DC). In some vehicles this unit also takes over while idling and may decide to shut the motor down.

The net result is that hybrids produce less tail pipe GHG and particulate emissions than a comparable capacity ICE vehicle. Later models also have electrical plug-in capability and are known as plug-in hybrid electric vehicle (PHEV). The advantage of a PHEV over the earlier purely electric vehicles is their overall range between refuelling/recharge. However this situation is changing rapidly.

The totally battery driven electrical vehicle (BEV) on the other hand relies solely on batteries for propulsion and regenerative braking. Understandably they also require plug-in capability for recharge either at a roadside facility or more commonly at the owner's residence.

Some experimental types have solar panels which charge their batteries. Electrical bicycles are also gaining popularity.

The required properties of vehicle propulsion batteries include:

- high power and energy to mass (weight) ratios,
- high energy density,
- low mass,
- ease of recharging

Compared to the high energy to mass ratios of petroleum based fuels the current range of batteries are relatively poor performers. As was noted in Chapter 2 petrol and diesel fuel has an inherent energy level of around 10 kWh/kg whereas the best vehicle propulsion battery on the market has around 200 Wh/kg or just 2% energy per kilogram to that of petrol/diesel.

While the cost of electricity to recharge a vehicle battery is fairly comparable to the current cost of a kWh extracted from a petroleum fuel, the conversion performance to mechanical propulsion of the electrical vehicle is far superior to the ICE vehicle. But the up-front cost of the battery bank is high and can represent as much as half the cost of the electric/hybrid vehicle.

Early electric vehicles used the traditional lead acid battery due to the advanced nature of that technology but their mass is high and energy density low. Further the overall life of the lead battery is only around 2 to 3 years and this can be reduced further if discharged regularly below 50%.

Nickel-Metal Hydride batteries have also been developed for vehicles. The have better energy density characteristics than lead-acid batteries and considerably longer life span but the energy
efficiency (chemical to electrical and vice versa) is somewhat less.

More recent developments have incorporated Lithium-ion batteries taking advantage of technology spin off from laptop and mobile phone battery development. Lithium is very much lighter than most elements and hence a considerable weight saving in respect to the total electrical vehicle mass. The Lithium-ion energy density is relatively high and adoption of nano technologies have made considerable gains in life of these batteries and the number of overall charge/recharge cycles. It is claimed that 7000 charges and 10 year life of the latest Lithium-ion battery set can be expected.103

A report by the US Electric Power Research Institute states that two BEVs, the Chevrolet Volt and Nissan Leaf outperform both hybrid and conventional ICE vehicles on overall cost.104 The Leaf is also reported to have an equivalent petrol consumption of 2.41 litres/100kms compared to 6-20 litres/100kms of conventional ICE vehicles.105

Fig. 10.1 The BMW i3 has a 130 km range between charges, recharges the 18.8 kWh Lithium Ion battery to 80% of full capacity within 20 minutes (3 hours for 100%). Courtesy: BMW
LCA of vehicles:
Just how well the BEVs etc., compare with ICE powered vehicles regarding energy consumption and emissions depends very much on the type of electric vehicle (BEV or PHEV), the source of the energy they used, i.e. the proportion of fossil fuel energy, as well as the type and throughput of the battery and its cathode material that is chosen. Even among vehicles that use the popular Li ion range of batteries there can be considerable differences in LCA performance to the extent that the energy consumption and GHG emissions per kilometre can be as high as 80% and 86% respectively of that of an ICE vehicle.  

Pros

- Development and production techniques are developing rapidly. While Lithium Ion batteries are the dominate technology at present constant research is being undertaken in a bid to improve battery performance and cost.
- Cost of battery packs are dropping dramatically. A typical sedan BEV requires around 150 to 200 kW capacity for 150 km mobility between re-charges. In 2014 prices were claimed to be well below US$300/kWh and dropping steadily by around 8% pa due both to technological advances and economies of scale.
- Battery performance continues to improve. Some BEVs consume as little as 1.4 litres/100km equivalent petroleum fuel while average USEPA suggests figures around 4 litres/100km for average country/city driving.
- Maintenance costs of BEVs is considerably lower than ICE vehicles and in some cases overall costs are lower.
- Many electric vehicles can outperform ICE vehicles on acceleration. They can convert approximately 80% of the chemical energy in the battery pack to mechanical propulsion whereas an ICE engine barely exceeds 25%
• Electric vehicles are quiet although this could be a disadvantage to some pedestrians. 'Noise' similar to say a V8 engine can always be added and likely to become an optional extra much the same as choosing a ring tone.

• The choice of electricity supply for recharging during an electrical vehicle operating life could eliminate GHG emissions except for those generated during the vehicle's manufacture. Some reports claim these manufacturing emissions can be much higher than those currently for ICE vehicles.

• For electric vehicles on charge there could be an advantage to power utilities to use this energy 'sink' to level out electricity peak lopping and only charge batteries in low demand times. This would be one of the benefits of the so called 'smart grid'.

• Some battery manufacturers are already claiming battery life will be 7000 recharges or 10 years. They can then be used as backup units for solar panels.

• A number of local councils and shopping centres are offering free recharge centres for customers with electric vehicles.

**Cons**

• While there is little or no GHG emissions penalty imposed on petroleum fuels some electric vehicles can be more expensive.

• Incorrect charging practices can cause safety issues such as fires.

• Extreme temperatures can affect the performance of some batteries.

• Availability of some battery raw materials such as nickel, lead, lithium and rare earth materials may decline over time.

• Currently recharge/battery exchange facilities are far less common than ICE service stations.

• Life cycle assessment (LCA) of Lithium Ion batteries can be confusing. Just to manufacture the Li-Ion battery provides a poor return - 870 to 2500 MJ/kWh battery capacity (EROI of between 0.0041 and 0.0014) and 60 to 150 kg CO$_2$e/kWh of battery capacity. On the other hand if we base this on the energy stored by the battery over its lifetime of thousands of recharges we may get a much more favourable result such as an EROI of 10. 

• As there is little in the way of waste heat from the electric motor additional heating equipment needs to be employed to warm the passengers during cold weather such as a heat pump (reverse cycle air conditioner).

• Recharging can take considerably longer than filling up the ICE tank. This can take anywhere between 30 minutes and 12 hours but no one needs to be present. However battery swaps are possible at some stations and with some types of BEVs.

**10.5 Fuel cells**

Fuel cells can be described as electro-chemical conversion units which can combine fuels (typically hydrogen) with oxidants (typically oxygen) to generate direct current electricity. While heat is also produced the efficiency of a fuel cell is considerably higher than that of a standard internal
combustion engine which is governed by the Carnot cycle

Fuel cells have been operating since 1839, much earlier than the internal combustion and steam turbine. First invented in 1838 by Christian Friedrich Schönbein in Basle, Switzerland it was Sir William Grove of Wales who, by using a primitive hydrogen fuelled/sulphuric acid electrolyte/platinum electrode combination developed what became the most popular fuel cell type - the Proton Exchange Membrane (PEM). As well as stationary electricity generators they have been used in motor vehicles, space vehicles and submarines.

In the year 2013 global manufacture of fuel cells grossed 180.5 MW of which 168.4 MW were stationary units. The market size is US$1.8 billion of which Japan has approximately 66%


Hydrogen atoms fed to the anode are ionised by means of a platinum catalyst into a hydrogen nucleus (proton) and an electron. The protons diffuse through the electrolyte membrane to the cathode. The electrons on the other hand cannot go through the membrane and are instead directed via the electrical terminals to the cathode thereby forming an electrical current much like a battery. At the cathode the proton, electron and oxygen in the air combine to form water and heat. This type of fuel cell is referred to as a Proton Exchange Membrane (PEM) unit. It will be noted the ideal electrical energy output represents 83% of the energy input but in reality 40% to 60% is achieved in practice. Nonetheless this is quite high compared to an internal combustion engine which rarely exceeds 25% efficiency.

Fuels other than hydrogen include reformed hydrocarbons e.g. methanol. As actual combustion is not involved in a fuel cell the emissions from the hydrocarbons are considerably less than from a conventional internal combustion engine.

The maximum theoretical voltage of a single fuel cell is only 1.23 volts. Efficiency losses can reduce this considerably to as low as 0.7 volts hence many such cells are banked together in stacks.
to provide adequate overall voltage to drive a vehicle.

The PEM fuel cells are one of only several types currently under development but currently represent 95% of all fuel cells manufactured. One currently in production is the zinc-air fuel cell which could be classed as a battery and button batteries are often of this concept. Required oxygen is accessed from surrounding air so they need to have an opening to the atmosphere. While this concept has been developed for vehicle propulsion by General Motors little advance of this has been made since the 1970s. Zinc-air fuel cells have the advantage of not requiring expensive platinum catalysts unlike PEMs which require around 100 grams for vehicular capacity fuel cells.

In 2007 Daihatsu developed an alkaline based fuel cell that avoids the use of platinum catalysts using cobalt or nickel instead. The Daihatsu fuel cell also has a higher theoretical voltage per cell than hydrogen at 1.56 volts. The fuel used is a liquid hydrazine hydrate (NH₂NH₂H₂O rocket fuel). While considered a replacement for the PEM cell for vehicles Daihatsu has now turned its attention to smaller units for home and outdoor use as backup electricity supplies. While the liquid fuel cells have density advantages over hydrogen they also have serious safety limitations and readily reacts with various metals causing combustion and the liquids are also toxic if ingested. With a useful heat value of 5.39kWh/kg it has far less inherent energy than hydrogen.

While the liquid fuel cells have density advantages over hydrogen they also have serious safety limitations and readily reacts with various metals causing combustion and the liquids are also toxic if ingested. With a useful heat value of 5.39kWh/kg it has far less inherent energy than hydrogen.

The first fuel cell car to be marketed in Australia, the SUV ix35, was launched by Hyundai in late 2014. The company has also stated it will also soon be producing and distributing hydrogen fuel using solar energy. Presumably additional hydrogen will be stored for overnight use when there is little or no solar energy.

**Pros**

- Highly efficient compared to the internal combustion engine
- Low emission fuel source
- Low noise
- Modular construction – a specific number of individual cells are made up into stacks to suit the output required.
- Various fuels can be used after suitable transformation can be used

**Cons**

- Fuel cells tend to be expensive and can require exotic materials
- Fuels are not freely available and those that are available need to be reformed from fossil fuels or electrolysis of water, which requires energy (Low EROI).
- Fuels need to be of high purity, and are difficult to transport and store
- Those operating at high temperatures such as Molten Carbonate and Direct Carbon suffer from degradation over time and require lengthy start-up times.
- It is not possible to maximise both power density and efficiency by design. At maximum power density the efficiency is only 50% of total.

- In 2012 there were only 208 hydrogen fuel cell refuelling stations, mainly in Europe and USA.

### 10.6 MHD

It may seem a strange topic for a chapter on transport but it is one that someday may become relevant to propulsion of some type of vessel.

Magneto hydrodynamic (MHD) generators use the flow of a conducting fluid in the presence of magnetic and electric fields to generate electricity. This fluid can be a high temperature gas (plasma), easily ionisable liquid salts of alkali metals such as sodium or potassium, or an inert gas that is injected (seeded) with some compound of an ionisable metal such as caesium. The first ever was created by Michael Faraday in 1831.

The basic principal is much the same as any electrical generator that uses the theory of an electric current being generated when an electric conductor moves across a magnetic field. The reverse is true of an electric motor. However instead of the electric conductor being a copper or sometimes aluminium coil of wire the MHD generator uses the conducting properties of the ionised gas or molten salt. Electrodes placed in the fluid conductor stream carry away the electric current induced which results in the fluid losing temperature and velocity.

![Fig. 10.4 Simplified concept of MHD](image)

While the principle has been around for some time their use has been limited to the present. The overall theoretical efficiency of a plant is predicted to be around 60% if MHD is combined with some other thermal or nuclear generating system but the efficiency for stand-alone units is little more than 17%.
A 28MW coal fired test rig was set up at White Bay power station near Sydney in the late 1970s as an upstream efficiency enhancer.

Cost per kWh seems to be the major disadvantage of MHD units; even when combined with conventional power station hardware and so they have largely been overlooked in favour of combined cycle power facilities. Even so as fossil fuels are phased out as they must be, they may come back into fashion when combined with some renewable or nuclear energy sources, especially as a replacement for conventional heat exchangers.

Pros

- MHD units can be used to improve overall efficiency of conventional power plants.
- They are relatively silent in operation and have been studied as means of submarine propulsion.
- They can be used as ‘closed’ Brayton type cycle using seeded inert gases thereby enhancing efficiency.
- They are favoured for being able to produce large electrical power pulses, a property which may find a role in the development of nuclear fusion.

Cons

- Development has not progressed far and so any partial replacement for fossil fuels may not be practical in the short term. The situation may well change later down the track.
- If alkali metals are used they are extremely reactive when exposed to water and can also react with structural components leading to toxic discharges.
The oldest and strongest emotion of mankind is fear, and the oldest and strongest kind of fear is fear of the unknown” H P Lovecraft. Supernatural Horror in Literature

11. Nuclear Fission

11.1 Fission Basics

The elements:

There are some 92 naturally occurring elements that make up our earth, although one called technetium is not found in any quantity as it decayed radioactively as soon it was formed. The elements comprise of gases (e.g. Oxygen, Hydrogen, and Nitrogen), metals (e.g. Iron, Lead, and Zinc) and solid non-metals (e.g. Carbon, Silicon, and Sulphur). A list of elements (the Periodic table) is available in Appendix 11.

As mentioned in earlier chapters they each have their distinct number of protons in the nucleus and the same number of electrical charge-balancing electrons orbiting at a distance. Each element also contains a certain number of neutrons in the nucleus. The number of neutrons can differ for the same element, creating ‘isotopes’ of the element, with the number of neutrons determining the element’s “isotopic” characteristics. Any isotope can therefore be identified by its Atomic number \( Z \), which is the number of protons, and its Atomic mass number \( A \), which is the combined number of protons and neutrons. For instance, the naturally occurring form of the element beryllium has 4 protons and 5 neutrons, and is designated as \(^{9}\text{Be}^6\).

![Fig. 11.1 Nomenclature regarding elements](image)

The number of protons (positively charged) determine the element. The number of neutrons (no charge) determines the isotope of that element. It has slightly greater mass than the proton. The number of protons and electrons determines its nuclear history and potential. The number of electrons (negatively charged) of a neutral atom of an element equals the number and charge of the protons therein but are have a much smaller mass. They are arranged in concentric shells of which the number of electrons in the outer shells determines how the element will react chemically.

Since the birth of the atomic age other so-called “post uranium” elements, have been created and found to have varying uses. One such element is Americium (\( Z=95 \)) which is used in very small amounts in smoke detectors.

Now you may recall the sketch below of a carbon 12 (\( Z=6 \)) atom from Chapter 4
This is a typical representational format of an atom consisting of varying quantities of electrons, protons and neutrons. An electron has a negative charge and is of very small mass compared to a proton which itself has an equal but opposite (positive) electrical charge. The neutrons have slightly more mass than a proton but as the name implies, they have no charge and, as mentioned above, can vary in number in any element, thus determining the 'isotope' of that particular element. You may recall that different isotopes of one element will behave similarly in chemical reactions but can behave differently in nuclear reactions.

Protons and electrons are in equal in number in the element's free, non-bonded form and hence the whole atom is of neutral charge.

Now the electrons determine the chemical reactions, if any, of the specific element such as during combustion of fossil fuels. The energy either produced or required during a specific chemical reaction involves transfer of electrons from one element to its partner. For instance, in the chemical reaction shown in Fig. 11.3 the four outer electrons of the oxygen atom are joined by the two from the two hydrogen atoms to form water $\text{H}_2\text{O}$, and releasing energy as heat.

A typical simple chemical reaction involving the transfer of the single electron of each of the hydrogen atoms to a single oxygen atom forming water. The reaction is exothermic meaning it gives off net heat rather than requiring same as in an endothermic reaction such as required to convert water back to its constituents. The energy required/produced by a nuclear reaction can be millions of times greater than that of a chemical reaction per event.
The energy comes from the binding energy of the electrons in the two hydrogen atoms as they are given up to the oxygen. This released energy is known as Binding Energy.

In contrast to chemical reactions, nuclear reactions, both fission and fusion, involve energy associated with the nucleus of an atom, specifically to its protons and neutrons. These reactions also involve a binding energy but one that is usually millions of times greater than that of a chemical reaction, hence the huge difference in the resultant energy released in nuclear reactions. Both reactions however are governed by Einstein's famous equation:

$$E=mc^2$$

Where $E$ is the energy emitted (Joules), $m$ is any change in mass (kg) and $c$ is the speed of light (almost 0.3 billion metres/sec). In any chemical or nuclear reaction where energy is released the total mass of the product(s) is somewhat less than that of its original component(s). In the case of chemical reactions the differential mass is usually too small to measure, but not so with nuclear fission or fusion. Hence, the resultant energy released in nuclear reactions is commensurably larger (basic nuclear energy calculations can be found in Appendix 11).

Now the 92 elements that make up the earth were all generated in the cosmos billions of years ago. Some are the result of nuclear fusion reactions (starting with hydrogen), and others are the result of nuclear fission taking place within exploding stars, known as supernovas. Fusion occurs when the nucleus of two elements combine, fission when one nucleus splits into two or more elements. Iron is usually regarded to have the most tightly bound nucleus (actually it is a nickel isotope $^{62}\text{Ni}$ but this is far less abundant than the close runner up iron $^{56}\text{Fe}$). Elements that have an atomic weight below iron are a result of fusion reactions. Elements above iron are believed to have been formed by a fission process following the massive neutron bombardment in the dying moments of a supernova, creating elements super saturated with neutrons which later decay to heavy elements that are fissile, or “fissionable”.

### Fission:

The vast majority of nuclear power reactors operating today do so by causing an isotope, mainly uranium $^{235}\text{U}$ to break up, i.e. fission. In other words the $^{235}\text{U}$ atom is broken down (split) into two, sometimes three so called fission products, or isotopes. While the bulk of naturally occurring uranium (99.27%) is the isotope $^{238}\text{U}$, which can and does split in a reactor, it is much less likely to split than with $^{235}\text{U}$ and its neutron yield is insufficient to maintain a chain reaction. Hence although fissionable $^{238}\text{U}$ is not classed as a fissile isotope and hence most fission reactors instead use $^{235}\text{U}$ as their main fuel source.
The reason we say typical is that the fission products shown as $^{141}\text{Ba}$ and $^{92}\text{Kr}$ could easily be two others from a wide spectrum of radioisotopes and in some cases with a third tritium, a hydrogen isotope $^3\text{H}$. Further the neutrons emitted which are essential to maintain a chain reaction in a reactor can vary 2 or 3 in number, average yield is 2.5. The radionuclide barium $^{141}\text{Ba}$ is a beta emitter of half-life of just over 18 minutes and is also a gamma emitter. It's so called daughter products finally end up as stable praseodymium $^{141}\text{Pr}$. Similarly the radionuclide krypton $^{92}\text{Kr}$ is a beta emitter of half-life just under 2 seconds. Its chain of decay finishes up at stable zirconium $^{92}\text{Zr}$.

The splitting of an isotope results from the capture of an extra neutron by the nucleus of the fissile element. The impregnated atom immediately becomes unstable and splits, usually into two radioactive elements (also termed fission products or radionuclide) which themselves decay by emitting radioactivity of one or two of the three possible forms (alpha, beta or gamma). The form and rate of an isotope’s radioactivity decay is specific to each particular isotope. In the case of $^{235}\text{U}$ two or three additional neutrons are released, which are available to create other $^{235}\text{U}$ fission reactions – hence we have a “chain reaction”.

One important aspect of an isotope’s decay pattern is its so-called half-life i.e. the time required for the radiation intensity of the particular radionuclide to halve. Depending on which radionuclide this can vary from seconds to thousands of years.

Fission probability and moderation:

While fission can take place through the a fissionable nucleus’ absorption of a neutron of any energy level (velocity) the probability of such an event is greatly increased if the neutrons emitted from one fission event are slowed down from millions of electron volts (>2MeV) to about 0.025 eV. The slower neutrons then have a much ‘bigger’ target in the fissile nucleus. As neutrons have no electrical charge the only method available is to create obstacles in the way of light atoms for the neutrons to collide with and impart some of their energy. Light atoms of fluids such as hydrogen,
helium and carbon are particularly equipped to perform this service, and are termed 'moderation'. The closer the mass of the atoms in a chosen moderator is to that of a fissile neutron, the faster the collisions will slow it down. The variable used to measure the probability of collisions is termed the 'cross section' and the unit is the 'Barn' (one trillion trillionth of a cm$^2$). Increasing a cross section is akin to zooming in on a target.

Of the nuclear fission reactor capacity operating today some 88.5% are termed Light Water Reactors (LWR), also known as Pressurised Water Reactors or Boiling Water Reactors. These use ordinary water H$_2$O as both coolant and moderator, the hydrogen in the water being mainly attributed for the moderation task as the mass of hydrogen atom is very similar to that of a neutron. Another 6.5% of nuclear power generated worldwide are termed Pressurised Heavy Water Reactors (PHWR) and use heavy water (deuterium oxide or D$_2$O). Deuterium is an isotope of hydrogen and is used as a moderator in PHWRs. In sea water an average of one hydrogen atom in 6240 is a deuterium atom. Unlike its more plentiful sister isotope deuterium's nucleus also has a neutron. While its relative scarcity is reflected in its price, because it is far less able to absorb a neutron it is 80 times more potent in conserving free neutrons while slowing them down.

Units that use moderators are called thermal reactors. But not all reactors rely on moderation in order to facilitate fission. So called Fast Reactors have been designed with varying degrees of success that rely in increased neutron density or flux to maintain the chain reaction. These usually adopt a fission isotope breeding regime whereby, rather than allow any surplus neutrons to escape into the surrounding reactor structure, they are captured by an intervening blanket containing so called fertile isotopes (e.g. $^{238}$U and $^{232}$Th), which when impregnated by a neutron usually transform into fissile $^{239}$Pu and $^{233}$U respectively, enabling chain reactions to take place.

To increase the odds of a chain reaction most thermal reactor are also designed to use enriched fuel i.e. the odds of a fission in the reactor core are enhanced by increasing the amount of $^{235}$U from 0.72% to somewhere between 2 and 5% of total mass. This is achieved prior to the fuel manufacturing process currently using a series of centrifuges). However some Fast Reactors can and do operate with the natural concentration of $^{235}$U.

Reactivity control:

Control of a nuclear reactor is almost always by way of the adjustment of a series of control rods which can penetrate the reactor core at various levels depending on the amount of reactivity required. They are automatically propelled to full core depth within a second in the event of an emergency such as an earthquake. Control rods are predominantly made up of non-fissile materials which have a very high absorption cross section, enabling them to effectively 'mop up' neutrons. One such material is an isotope of boron $^{10}$B. The design of their drive mechanisms are such that they cannot be accidentally or deliberately fully removed from an active core, thus preventing excessive reactivity and potential meltdown. In some LWRs chemical combinations of $^{10}$B are used in dosing of the water for finer control over reaction rates.

The so called “reactivity” of a reactor is a measure of whether there is a decline in, build up, or steady state in the number of 'roaming' neutrons in the reactor core. It is basically an indication of how many neutrons are available to continue a chain reaction after losing some to absorption or complete escape from the core. While it is impossible to count actual neutrons in the core at any one time a type of analogue instrument is used which measures a small amount of radionuclides generated in the instrument's chamber. Control rods are moved in and out of the core to achieve whatever reactivity is required i.e. the more exposure the control rods have to the free neutrons in the core the more they absorb them and thus decrease the reactivity. There are also backup systems including fluid injection of neutron absorbers in place.
Regardless of the level of $^{235}\text{U}$ enrichment used in reactors a “nuclear explosion” cannot possibly occur. Nuclear weapons need over 80% fissile isotopes in a supercritical mass geometry and a dearth of neutron capturing isotopes to create a nuclear explosion, none of which are inherent in any type of reactor’s design. This, of course does not deflect from the seriousness of the three major accidents already witnessed at nuclear plants around the world. But in none of these cases was a nuclear explosion witnessed, nor could it be. The explosion at Fukushima was due to hydrogen (chemical) explosions resulting from cooling water decomposition. Those at Chernobyl was firstly due the excess steam generated in the core and then one most likely due to hydrogen formation.

**Fuel construction:**

Fuels range from natural uranium metal, enriched $\text{U}_2\text{O}_3$, uranium carbide and so called mixed oxide (MOX) - a blend of uranium and recycled plutonium as an oxide. These are then clad in some low adsorption moderator materials such as zirconium, magnesium oxide, ceramics etc.

**Spent fuel reprocessing:**

The fission products are contained where they are formed, within the fuel assemblies (rods, spheres etc.) When a fuel assembly reaches its peak 'burn-up' it is removed either singularly or as part of a batch and inserted in a specially designed pond of cooling water, usually located at the reactor site, where it remains for several years to allow short half-life isotopes to decay away. In the USA the spent fuel rods are then simply buried in special purpose bunkers, mainly located in Idaho and South Carolina. There, reprocessing of spent fuel was originally considered financially unattractive but in 1977 a bill was passed by Jimmy Carter to prevent reprocessing in a bid to deter terrorist groups obtaining the fissile plutonium $^{239}\text{Pu}$ built up during operation. So far more than 70,000 tonnes of nuclear waste has been buried in the US.\(^{110}\) Interestingly to quote the Nuclear World Forum 'the materials potentially available for recycling (but locked up in stored used fuel) could conceivably run the US reactor fleet of about 100GWe for almost 30 years with no new uranium input.'\(^{111}\)

In other countries such as France, Japan, Russia and Britain fission waste is recycled as a resource for more fuel and a considerable reduction in waste deposits. Facilities have been built to reprocess spent nuclear fuel and extract the unburned uranium and the generated plutonium which are then used to form new mixed-oxide (MOX) nuclear fuel contributing to 25 to 30% more energy resource. Some useful fission products and cladding materials can also be salvaged. In the process the actual amount of waste product to be disposed is as low as one fifth of the original.

The plutonium is almost immediately recycled as a MOX fuel to reduce the risk of falling into the hands of potential terrorists and states not signatory to the Non Proliferation Treaty. About 90,000 tonnes of spent fuel have so far been reprocessed.

**Nuclear proliferation:**

There is a natural concern in many quarters that the existence of nuclear power reactors can lead to nuclear proliferation. While the level of $^{235}\text{U}$ used is far too low to be of use as a weapon there is a by-product of $^{238}\text{U}$ neutron capture that can be extracted from the spent fuel rods and used to manufacture a bomb. This is a plutonium isotope $^{239}\text{Pu}$, a man-made material not found naturally. It was used in one of the two bombs dropped on Japan in WWII. Highly enriched $^{235}\text{U}$, which cannot
be produced in a reactor, was used in the other bomb, was produced in a gaseous diffusion separation facility in the US. Both India's and Pakistan's nuclear arsenals are based on plutonium derived from reactor designs adapted from those supplied by the West.\textsuperscript{112, 113}

Much discussion has taken place in recent times of reintroducing thorium based reactors following their abandonment by the USA after trials in the 1950s. Thorium is not fissile but a fertile thorium isotope can produce the fissile \textsuperscript{233}U once it has absorbed a neutron. The reasons for considering thorium based reactors include thorium's great abundance and it's potentially lesser suitability as a bomb material. However, there are ways round these deterrents and one, albeit small thorium based \textsuperscript{233}U bomb, was exploded by India in May 1998.\textsuperscript{114, 115}

Along with the threat of wilful misuse of fissile material for bomb manufacture by some entities there is also the threat of highly toxic fission products being obtained by terrorist groups from spent fuel rods. Handling and deployment of such material presents a real challenge to non-professionals but nonetheless this is a risk that must be taken into account.

Given these factors it would seem sensible for Australia to develop a nuclear fuel cycle industry rather than lease its considerable reserves of uranium and thorium rather than just mine and sell it. In this way Australia could shoulder the responsibility and take charge of the nuclear by-products. Leasing of nuclear fuel has been suggested by a number of clear thinkers in recent times.\textsuperscript{116, 117}

Centrifuge enrichment of uranium has replaced gaseous centrifuge due to energy savings, among other reasons. The possession of centrifuge enrichment by Iran in recent years has caused concern in the West. While it is claimed that their facilities are only for independent reactor fuel manufacture the same equipment can be used to manufacture weapons grade uranium.\textsuperscript{239}Pu extracted from normal thermal reactor spent fuel is highly 'contaminated' with \textsuperscript{240}Pu which is highly radioactive and creates problems for any would be terrorist. Weapons grade plutonium has been extracted from low burn-up reactor fuel and requires deliberate early fuel extraction. Hence the plutonium locked up in say the US spent fuel storage at Yucca Mountain in Nevada would not be much of an attraction to potential thieves.

**Nuclear radiation:**

The other forms of radiation beside neutron emissions are alpha, beta and gamma radiation, which are all emitted at varying energies, depending on the radionuclide. The alpha is a relatively large particle of two protons and two neutrons simulating the nucleus of a helium atom. It is emitted from the nucleus and as such converts the radionuclide into another whose nucleus has two fewer protons and two fewer neutrons. Unless such an alpha emitting radionuclide is ingested there is little risk of health as one can be stopped in its tracks by a sheet of paper.

Similarly, unless the source is ingested into the body, a beta particle (which is identical to an electron) can be stopped by the epidermis of the skin or just a sheet of aluminium foil.

Gamma radiation however is emitted as an electromagnetic wave and depending on its energy can penetrate thick sections of concrete, metals, etc. For this very reason radionuclides with high energy gamma radiation are used to 'X-ray' welds on ships and bridges etc., for integrity checks.

High energy gamma emitting radionuclides with long half-lives constitute the high level nuclear waste we may read about which when isolated in a nuclear waste recycle facility are usually encased in a glass cube and buried deep in stable strata. Other experiments have taken place to transmute some highly radioactive isotopes such as the iodine isotope \textsuperscript{129}I, which has a half-life of over 15 million years, into one which is far less onerous. Fast neutron reactors are more efficient at this task but there are costs involved in respect to additional fuel requirements and time.\textsuperscript{118}
If one is unfortunate to ingest radioactive material then all three types of radioactivity can have an impact. For instance the thyroid gland attracts iodine and if a person say, drinks milk that has been contaminated with radioactive iodine $^{131}$I, which is both a beta and a gamma emitter, then it can cause serious damage to that organ. $^{131}$I was largely responsible for much of the child thyroid cancers following the Chernobyl incident, as communications instructing mothers not to feed babies with local milk was lacking. Dairy cattle in the area feeding on grass contaminated with $^{131}$I would give contaminated milk and iodine itself concentrates in the thyroid.

The forgoing is a very brief snap shot of nuclear fission and radiation health effects and is in no way meant to cover the vast area of the these sciences. Further reading is to be encouraged.

![Distribution of fission products from Uranium-235](image)

Fig 11.5: The possible spectrum of radioisotopes generated by the fission of $^{235}$U

<table>
<thead>
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<th>Mass number, A</th>
<th>Percentage</th>
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<td>90-100</td>
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<td>100-110</td>
<td>1.6</td>
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<td>110-120</td>
<td>0.1</td>
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<tr>
<td>170-180</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The atomic mass number $A$ is the total count of nucleons (i.e. protons and neutrons) in an atom's nucleus. For instance the one for $^{235}$U is 235 which has 92 protons and 143 neutrons. As will be noted from those radioisotopes of Fig 11.4 these are marked here. But there could be any combination of two radioisotopes generated whose combined mass, along with those of the emitted neutrons, fits the $E=mc^2$ equation. In fact in some rare cases tritium radioisotope of hydrogen with $A=3$ can also form a third partner.

**Natural uranium:**

Naturally occurring $^{235}$U constitutes only 0.7200% of uranium. The balance is mainly $^{238}$U at 99.2745% and a small amount of $^{234}$U at 0.0055%. The $^{235}$U atom is an alpha emitter of energy 4.68 MeV (2.08E-19 kWh) with a half-life of 0.7 billion years which, due to losing its alpha particle, naturally decays to thorium ($^{231}$Th) itself a beta emitter with a half-life of just over one day that decays to protactinium ($^{231}$Pa) with a half-life of 32,788 years. This chain of decaying radionuclides (daughter products) continues until the chain reaches stable lead $^{207}$Pb. $^{119}$ $^{234}$U and $^{238}$U decay in a similar manner with different half-lives but finally the chain finishes up as stable lead $^{206}$Pb. Most of the daughter products of uranium also emit gamma radiation.

**What form does the fission energy take?**

The immense amount of energy released from a fission reaction materialises in the form of kinetic
energy carried by the fission products. The distribution of these energies is proportional to the mass and quantity of like products. The lighter neutrons will each have greater velocity relative to the heavier radioisotopes due to the law of conservation. This kinetic energy is converted to heat as the various fission products collide with reactor vessel coolants and structures. This is then largely absorbed by the reactor coolant which is most commonly (light) water, but can also be a gas (e.g. CO₂), and in some cases a molten salt or metal. It is then usually converted to steam to drive a steam turbine.

### 11.2 Types of reactors

Table 11.1 lists the basic types of reactors currently in operation. By far the majority are so called thermal reactors that use a moderator to slow down free neutrons. Of these, most common are the pressurised (light) water reactors (PWRs) with over 65% of the total. Followed by boiling (light) water reactors (BWRs) at over 18% and pressurised heavy water reactors (PHWRs) at just over 11%.

The PWR and BWR reactors were both developed in the USA in the late 1950s. They use ordinary light water as coolant and moderator, and uranium oxide fuel pellets slightly enriched in \(^{235}\text{U}\) and clad in zirconium. The major difference in the two designs is their operating pressure. As the names suggest the coolant in the BWR is allowed to boil, albeit at an elevated pressure (about 7MPa) while that of the PWR does not boil due to its increased vessel operating pressure (about 15MPa). This means there has to be a secondary ‘steam’ circuit for the PWR whereas one is not required for the BWR. The primary coolant flow rate of the PWR needs to be considerably higher than that of the BWR and up to four primary loops are incorporated depending on plant capacity. Both types have overall efficiencies (Electrical output to Nuclear input) of around 34%. Refuelling takes place using remote handling equipment every 12 to 18 months when the reactors are shut down and up to a third of the spent innermost fuel rod assemblies are removed and transported to the cooling ponds while the outer partially spent fuel rods are moved into the centre.

Continual development of both types of reactors has taken place and some countries have adopted their own light water reactor designs including several European countries plus China, Japan, South Korea and the Russian Federation.

Steam temperatures and pressures are somewhat lower than most thermal (fossil fuelled) power stations and hence the turbine units in nuclear reactors tends to be somewhat larger. There is a supercritical light water reactor (SCWR) being designed as part of the Generation IV program but its demonstration timeline is currently somewhere between 2025 and 2030. ¹²⁰
As will be seen from Table 11.1 thermal reactors exceed fast breeder reactors by 218:1 and of those PWR reactors dominate the field in both quantity and capacity.

### Pressurised (light) Water Reactors (PWRs):

![Schematic diagram of a PWR power station](https://areva-np.com)

**Table 11.1: The world’s nuclear fission reactors as of 2015. Courtesy: European Nuclear Society**
The containment building enveloping the nuclear components of the power plant is now a universal concept. Chernobyl's reactors, now all shut down, had no containment building. Other RMBK type reactors still operate in Russia, some retrofitted with partial containment buildings. The latest Russian plants are PWRs. The primary coolant circuits of a PWR is maintained at high pressure by the use of steam in the pressuriser vessel so the (light H$_2$O) water never boils. The heat is then transferred to a secondary water coolant circuit to generate steam for the, more or less conventional steam turbine generator plant.

Power capacity of PWR units range from 10 to 1,500 MWe. Smaller units, along with some fast neutron reactors are used to propel ships and submarines.

In a typical 1100 MWe PWR there are 193 fuel rod assemblies, each having 264 fuel rods, and each packed with slightly enriched UO$_2$ pellets inside low neutron absorbing zirconium cladding. There are nearly 51,000 fuel rods or just over 86 tonnes of fuel in all.

Each fuel rod assembly has 24 control rod guides. The control rod assemblies are introduced from the top of the core and have to be removed after cold shut-down for refuelling operations. In the event of a loss of electrical power they automatically drop and shut the reactor down instantly.

In the event of any malfunction of the control rods there are back-up provisions such as core fluid injection using boron compounds.

The power capacities of BWRs range from 15 to 1,325MWe.

Typically in an 1100MWe BWR there are 764 fuel rod assemblies that each have 74 fuel rods. As per PWRs the fuel is slightly enriched UO$_2$ in zirconium cladding.

The 37 geometrically spaced boron nitride control rods are introduced hydraulically through the base of the core avoiding the need to remove them during refuelling. In the event of a loss of electrical power they automatically rise and shut the reactor down instantly. BWRs have similar back-up shut-down systems to PWRs.
Control rods are both boron carbide for emergency shut-down (scram) and silver-indium-cadmium for reactivity fine tuning.
Boiling (light) Water Reactors (BWRs):

The primary coolant circulation is enhanced by internal jet pumps. The resultant steam does become slightly radioactive primarily of $^{16}\text{N}$ with a very short half-life (7 seconds) enabling maintenance shortly after shut-down.
Unlike the PWR these control rods enter from the bottom of the core hydraulically. Emergency trip (Scram) is also automatic by the release of stored hydraulic energy.
Pressurised Heavy Water Reactors (PHWRs):

Pressurised heavy water reactors have continually been developed in Canada from the late 1950s. They are called CANDU reactors (an acronym for CANada Deuterium Uranium). There are currently 34 CANDU reactors plus several similar concepts especially in India simply named PHWRs in operation world-wide. A proposal to build one in Australia under the PM John Gorton administration at Jervis Bay in the 1970s. It was termed a Steam Generating Heavy Water Reactor (SGHWR) and the artist's concept was to have it appear like a sub-tropical village.

PHWRs of all types have two major differences to the light water reactors includes on-line rather than batch type refuelling and the use of heavy water (deuterium oxide D\(_2\)O) in place of light water (H\(_2\)O) as the moderator and usually as the primary coolant fluid. Although we say usually, the primary circuit coolant is sometimes light water as per the SGHWR.

Both these features give PHWR fundamental advantages over light water reactors. Firstly, there is no need to shut down every 12 to 18 months to refuel and secondly there is a possibility to use natural uranium (as UO\(_2\)) rather than having to firstly secure enriched uranium. The latter comes about by the fact the D\(_2\)O is as mentioned about 80 times more effective than H\(_2\)O as a moderator. Although the deuterium atom is more than twice the mass of its sibling isotope hydrogen and requires virtually twice the number of collisions to slow a neutron down to so called thermal energy, it absorbs infinitely less neutrons. In fact the heavy water purity has to be maintained as even a 0.5% H\(_2\)O contamination could cause the reactor to shut down.\(^{121}\)

---

**LEGEND**

1. Fuel bundles.
2. Calandrai (reactor core vessel).
3. Control rods.
4. Primary circuit (heavy water D\(_2\)O) pressuriser.
5. Heat exchanger.
7. Primary circuit (heavy water) pump.
8. On-line charge/discharge machines.
9. Moderator (heavy water).
10. Pressure tubes (380 to 480 in Zirconium).
11. Steam circuits to conventional turbine.
13. Nuclear island containment vessel.

---

Fig 11.10 Schematic representation of a CANDU reactor (nuclear island)
A disadvantage, and one often broadcast by light water reactor proponents was the cost of D\textsubscript{2}O being several times the cost of single malt Scotch. Canada has history of D\textsubscript{2}O production going back as far as WWII and the concentration of deuterium in the colder Arctic Ocean regions is quite high compared to the world average. Canada along with India are now the world's suppliers of heavy water. The initial heavy water inventory and losses do form a considerable portion of overall capital and operating costs. Notwithstanding, depending on the ground rules PHWR can be competitive with those of equivalent sized coal fired plants.\textsuperscript{122}

There is one type of PHWR that does not fit the calandria/pressure tube concept however but is no longer in vogue. There are two originally Siemens designed pressure vessel units in Argentina.

Two of the three PHWR in Argentina are of Siemens pressure vessel design (335 & 700 MW). Prior to the second Siemens unit being fully constructed Siemens themselves withdrew from nuclear design work and the this unit was finally completed in 2012 using new funding released by the Argentine Government and with technical assistance from Atomic Energy of Canada. Meanwhile a 648 MW CANDU6 was commissioned in 1984.

Fig. 11.11 The schematic layout of Siemens design PHWR
Gas Cooled Graphite Moderated Reactors (GCRs):

Gas cooled graphite moderated reactors are a distinctly British design although one advanced version so called High Temperature Graphite Reactor (HTGR) was built at Fort St, Vrain in Colorado and operated between 1979 & 1989 330MWe

The forerunner of the gas cooled designs were termed MAGNOX which used natural uranium metal fuel clad in magnesium oxide. If act one of the first even power reactors to feed energy to a grid (1957) was the 50MWe Calder Hall MAGNOX in Cumbria, UK which was also used to produce weapons grade plutonium. Of the 28 MAGNOX reactors built including one each in Japan and Italy as of 2016 all have been shut down, the last being one of the two (540 MW) units at Wylfa, Anglesea UK which close 30th Dec 2015 after 45 years of operation. The coolant used was CO₂ and supported on-line refuelling. The graphite (carbon) atom is far larger than that of a neutron and hence the relative size of the reactor was far larger than a comparable LWR. They have been rather good work horses, several operating for 40 years and over.

Experience gained was the stimulus for the British Advance Gas cooled Reactor (AGR). Retention of MAGNOX concepts included CO₂ cooling, on-line refuelling and from the later designs, post stressed concrete pressure vessels. Advances on their predecessors include superheated steam conditions allowing for conventional turbo-generator sets similar to those found in fossil fuel units which required up to 3.5% ²³⁵U enriched uranium as UO₂ in stainless steel cladding. Because of the volume of graphite needed compared to water these gas cooled reactors have a large footprint in civil works in particular which contributed to their higher unit costs.

As well as all 58 French (PWR) nuclear plants, company EDF now owns and operate all UK's 15 nuclear plants including 14 AGRs and the 1,198 MWe PWR which was commissioned in 1995, a milestone most probably signalling the termination of any further gas cooled thermal reactor development although a gas cooled fast reactor (GFR) study forms part of the Generation IV six reactor concepts exercise mentioned later.

![Fig. 11.12 Schematic of an AGR reactor](image_url)
Light water graphite reactors (LWGR):

The LWGRs was one of two preferred reactor concepts of the USSR developed in the 1970s principally as both a plutonium (weapons) and power reactor. The other is a type of fast breeder reactor (FBR).

Known as type RBMK (Reaktor Bolshoy Moshchnosti Kanalnyy), the thermal design was unique as it had some characteristic of both a BWR and a CGR. The reactor involved in the Chernobyl accident was of RBMK design mentioned later (see Accidents below and Appendix 11). As can be seen from Fig 11.13 it has a once through (light water) cooling circuit passing through the graphite moderator via pressure tubes.

The fuel is slightly enriched UO$_2$ clad in zirconium tube rods 3.65 metres in length. 18 such rods make up a bundle and there are 2 bundles per pressure tube. The pressurised cooling water boils in the tubes and the steam is extracted in the steam generators before being directed to the steam generator set. A helium/nitrogen gas mixture between the graphite and pressure tubes enhances heat transfer from the moderator generated by the neutron energy dispersal.

Refuelling takes place on line after isolating the respective pressure tube.

The control rods are of boron carbide, the main group of which insert from the top of the core while a shorter version are inserted from the bottom to help balance the power distribution.

Each of the two coolant loops feed has its own turbine generator totalling 1000 MWe station capacity.

![A Light Water Graphite-moderated Reactor (LWGR/RBMK)](image)

Fig.11.13 Schematic of the USSR LWGR (RBMK)

Note there is no real containment building. There were also some undesirable features some of which have been address since Chernobyl including a form of containment on the remaining 9 or so units in operation which are all still operating in Russia. Those in the Ukraine and Lithuania have been shut down.

Fast Neutron Reactors (FNR):

Now if the moderator is excluded, neutron absorber control equipment fully functional and sufficiently adequate fissible fuel per unit volume then it is possible to create a sustainable chain reaction with so called fast neutrons (1 to 10 MeV). The fast neutron fission cross sections are much
smaller than those for thermal neutrons but the neutron flux density, in other words enrichment, therefore needs to be much higher. Further with neutron energies above 1 MeV (4.45E-20 kWh) the vastly more common $^{238}\text{U}$ isotope and all plutonium isotopes are directly fissionable plus other trans-uranium elements (actinides - neptunium (Np) americium (Am) and curium (Cm) which have been produced in the thermal fission process and all with long half-lives can also be fissioned). This means that the energy derived from the same mass of fuel is considerably higher (about 60 times) than that of thermal reactors,

Basic differences then between thermal and fast reactors is as per Table 11.2

<table>
<thead>
<tr>
<th>Issue</th>
<th>Thermal reactor</th>
<th>Fast neutron reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usable neutron energy</td>
<td>Approx 0.025 eV</td>
<td>1 to 10 MeV</td>
</tr>
<tr>
<td>Moderator</td>
<td>Required. Light elements, water, heavy water, graphite</td>
<td>None</td>
</tr>
<tr>
<td>Coolant</td>
<td>Light elements, water, water, heavy water, CO$_2$ or helium gas</td>
<td>Low neutron absorbent, high specific heat, single phase gases, molten metals or salts. Currently in operation all use sodium.</td>
</tr>
<tr>
<td>Fuel</td>
<td>$^{235}\text{U}$ enriched metals or oxides or mixed oxide ($^{238}\text{U}$ &amp; $^{239}\text{Pu}$) MOX</td>
<td>All uranium, plutonium isotopes plus trans-uranium elements. Can be recycled thermal plant spent fuel after most fission products are removed. Metals, oxides, carbides and nitrides</td>
</tr>
<tr>
<td>Primary control</td>
<td>Control rods containing boron</td>
<td>Control rods containing boron</td>
</tr>
<tr>
<td>Breeding possibility</td>
<td>Conversion to fission breeding ratio usually around 0.6 but the US DOE's LWBR reached 1.01 using $^{233}\text{U}$ and fertile $^{232}\text{Th}$</td>
<td>Possible to produce more fuel than consumed from fertile uranium or thorium. (Breeding ratio up to 1.45)</td>
</tr>
<tr>
<td>Quantity of natural uranium consumed</td>
<td>1%</td>
<td>Theoretically 100%</td>
</tr>
<tr>
<td>Thermal efficiency %</td>
<td>34</td>
<td>35 to 44</td>
</tr>
<tr>
<td>Transmutation capability of long lived radioisotopes</td>
<td>Limited $^{231}$</td>
<td>Possible over time (years) but with extra fuel consumption. $^{234}$</td>
</tr>
<tr>
<td>Destruction of nuclear weapons grade U &amp; Pu capability</td>
<td>Yes but not without considerable difficulty</td>
<td>Yes</td>
</tr>
<tr>
<td>Load following capability</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Typical availability factors</td>
<td>90%</td>
<td>50 to 80% depending on which unit. The earlier units where largely experimental</td>
</tr>
<tr>
<td>Power density of core kW/litre</td>
<td>LWR 104, AGR 3</td>
<td>300 (Monju) to 550 (BN 600)</td>
</tr>
<tr>
<td>Reactor years operational experience</td>
<td>16,000</td>
<td>400</td>
</tr>
<tr>
<td>Typical steam temperature Deg C</td>
<td>275 (PWR) 541 (AGR)</td>
<td>505 (BN 600)</td>
</tr>
<tr>
<td>Typical steam pressure MPa</td>
<td>6.2 (PWR) $^{125}$ 17.3 (AGR) $^{126}$</td>
<td>14.4 (BN 600)</td>
</tr>
</tbody>
</table>

Table 11.2 Thermal and fast neutron reactor comparisons

By comparison steam conditions for the Bayswater coal fired plant in NSW are 540 $^\circ$C and 16.55 MPa similar to the AGR.
More modern, so called super and ultra-critical (steam above 374 °C and 22 MPa) plants where there is no phase change (steam/water) have much higher steam conditions and hence higher efficiency.

Fig. 11.14 Typical fast neutron reactor vessel (liquid metal pool type coolant)

Some FNRs are pool type with heat exchangers internal to the vessel. Others are circuit type similar to LWRs. All current fast reactors use liquid sodium as the primary and secondary coolant in line before the steam circuit. Annual refuelling is the norm. Initial fuel is usually a MOX or enriched uranium. For breeding more fuel the core is usually surrounded by a blanket of natural or depleted uranium or thorium which excess neutrons escaping the core converts to $^{239}$Pu and $^{233}$U respectively. If more fuel is produced than used the fast neutron reactor is termed a fast breeder reactor (FBR).

These reactors have the capability to use spent fuel extracted from thermal reactors fuel rods. Experiments in transmuting highly radioactive fission products with long half by neutron absorption into less potent radioisotopes is under way also although little information seems to be available in the public domain as to effectiveness of this. Nonetheless designs are afoot to have the fuel recycling plant integral with future nuclear plant.

Another prospect is that weapons grade uranium and plutonium that has been stockpiled both in the West and East can be and is being effectively be 'burnt' as fuel in a fast neutron reactor producing electricity, which if completed would be a blessing for mankind. Reportedly there is somewhere around 112 to 120 tonnes of weapons grade plutonium stored in the UK alone and enough to cater for the UK's energy supply for 500 years. Proposals for two units of a GE Hitachi designed fast sodium cooled fast neutron reactor to be built at Sellafield in the UK to tackle such an issue. This would be coupled to a single 662 MW turbine generator linked to the grid. The notion would be to partially irradiate the plutonium so that batch would contain highly radioactive fission products rendering it somewhat similar to spent fuel and very unattractive to would-be terrorist groups. It could then be stored along with other fission products and the whole so called 'spiking' process would take approximately 5 years to complete.

The alternatives are to:
- Convert it to MOX fuel for use in thermal reactors. The manufacture of MOX has been a costly and complex experiment for the UK
• Build more fast-neutron reactors and adapt it as a fuel which would be a much simpler process than MOX.

Loss of coolant does not present the same problem in an FNR as in a thermal reactor as in an FNR the fission process tends to slow down as the fuel temperature increases giving the control rods more leverage. On the other hand FNRs have been costly to build and operate compared to their thermal nuclear partners. That however could change with scale and increasing uranium costs.

Due to the small fission and absorption cross section presented to fast neutrons their targets opportunities need to be increase proportionally. Hence the fuels need to be more highly enriched (>20% as opposed to 1 to 5% for thermal). This may raise security concerns.

All operating FNRs use liquid sodium as the coolant. Other metals including mercury, lead, tin and a sodium-potassium alloy have also been used in the past. Sodium ticks most of the boxes by way of its low melting and high boiling points, small adsorption cross section, heat transfer and corrosion properties etc., however it is extremely reactive when in contact with air or water, as may have been demonstrated at one of your chemistry lessons in the past. It also becomes radioactive while in the core. As a result any exposed surface such as in a pool type FNR must be covered with an inert gas such as Argon. The radioactivity, although of short half-life dictates there be an intermediary sodium circuit between it and the steam generator. Regardless the Russian BOR-60 and BN-600 plus the French Phenix FNRs, all with sodium cooling, have each operated for well over 30 years with few sodium reaction incidents being openly reported. Concepts using other coolants, including gas, lead and molten salt as well as sodium are being studied as part of the so called Generation IV International Forum (GIF) involving some thirteen members.

**Generation IV R&D:**

In 2001 nine founding members, Argentine, Brazil, Canada, France, Japan, South Korea, South Africa, UK and USA signed a charter to cooperate in developing the next generation of nuclear reactors. Since then these have been joined by Switzerland, China, Russian Federation and Euratom.

A total of six concepts have been selected four of which are fast breeder concepts and the other two are of advanced thermal constructs. Advantage is being taken of past and existing reactors data as used in various experiments, prototypes plus computer models.

The key aims are to provide ultra-safe operation, modular sizes, high efficiency, and in fast neutron versions the ability to use thermal nuclear spent fuel and conversion of long lived actinides to fission products of far less half-lives, the longest of which would that of an isotope of caesium $^{137}$Cs reducing half-lives from literally millions of years to just over 30 years.

Three of the concepts are shown below:
Pressurised helium cooling, highly efficient gas turbine (Brayton Cycle), break even (1.0) breeding and closed cycle spent fuel recycling are the aims. An experimental GFR is being planned named ALLEGRO by the Czech and Slovak Republics, Hungary and Poland. Planned demonstration timeline 2024 to 2030
Lead or lead-bismuth alloy cooling at atmospheric pressure, steam or possibly highly efficient gas turbine (Brayton Cycle), closed cycle spent fuel recycling are the aims. Lead has no adverse reaction with air or water. Prototypes include Europe's ELFR, Russia's BREST-OD-300 and SSTAR. Planned demonstration timeline 2022 to 2030.

Molten Salt Reactor (MSR)

Fig. 11.17 Schematic of Generation IV's molten salt reactor

Molten salt reactor technology has been around for more than 50 years. The current study has two branches, one to use fissile material dissolved into the molten fluoride salt and the other to introduce coated particle fuel. Emphasis will be on adopting a fast neutron spectrum hence no moderator is required. Planned demonstration timeline 2022 to 2030


11.3 Accidents

Following three major incidents in existing nuclear fission plants in the last thirty five years building new ones could seem to be something that should be avoided at all costs. So if Australia could possibly get by without them and with a stable electricity network, maybe this is for the better. The more attractive nuclear fusion reactors are still very much in their development stage and at present levels of stimulus, impetuous and budgets suggests there is unlikely to be a commercial fusion plant within the time frame available before we have reached our Carbon Budget emissions limit. And, given a small number of accidents, nuclear fission plants have had a cumulative
operating life of over 15,000 years and generated over 74 trillion kWh of energy since the first nuclear kWh was generated in 1951. As of 2015 there are 438 operating reactors world-wide with a combined net capacity of 65,000 MWe. Most operate as high capacity base load plants with capacity factors of up to 80% and higher. When commercial nuclear fusion plants become a reality the fission stations will likely be decommissioned in much the same way as fossil fuel plants need to be, so this nuclear source of pollution can be curtailed.

**Fukushima:**

The frenzy of media coverage following the jaw-dropping images of an exploding reactor containment vessel on television seemed to overshadow the impact of earlier news clips showing the tsunami's devastating destruction of the region. There exists several conflicting figures in the media as to the actual death toll due to the Fukushima nuclear disaster and one claimed nuclear-related deaths reach as high as 1,232 in 2014 alone in the Fukushima Prefecture. But they describe the term 'nuclear-related' deaths as meaning “a death that does not result directly from radiation exposure but is caused by a disease later caused by exposure”.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in their 2013 Fukushima report specifically states “No radiation-related deaths or acute diseases have been observed among the workers and general public exposed to radiation from the accident.” UNSCEAR produced a follow-up White Paper in 2015. It examined 79 additional reports and found that “None materially affected the main findings in, or challenged the major assumptions of the 2013 Fukushima report but twelve were identified that had the potential to do so, albeit subject to further analysis or confirmation from studies of better quality.”

Nuclear fission reactors generate heat long after shut-down due to radioactive 'ash' material that builds up in the core's fuel rods over time and the core must be cooled by continuation of flow in the primary cooling circuit for several days or weeks after a shut-down, or until a 'cold' shut-down can be established.

Now it may seem to some that nuclear plants are much denigrated by renewable energy pundits while it would be prudent to treat it as a partner in many parts of the world to combat the greater threat of climate change. Most recently many of us witnessed media footage of three of the six Fukushima Daiichi reactors exploding due to hydrogen released from dissociated water (steam) coming in to contact with overheated fuel rod claddings following the magnitude 9.0 earthquake and subsequent tsunami in March 2011. All 11 reactors operating in the area when the earthquake hit were shut down automatically. Subsequent inspection showed none of these had been severely damaged by the earthquake itself but almost an hour later when the 15m high tsunami hit, units 1 to 3 at the Fukushima Diiichi plant lost their emergency power plants that were required to maintain power to the core circulation pumps. The grid connection had been severed and 12 of the 13 backup generators were disabled, preventing cooling water circulation from being maintained. It took 4 days to bring units 1 to 3 to cold shut-down. Unit 4 which had not been operating was also damaged due to the hydrogen explosions. Despite the graphic footage and difficulties experienced by local residents there have been no deaths or radiation sickness attributed to the explosions or the released radiation, although over 1,000 deaths have been attributed to a government-mandated evacuation lasting longer than necessary.

According to one independent consultant, Willem Post, PE, University of Connecticut the risk of deaths from the fossil fuels that are being used to replace Japan's shut down nuclear plants will far
outweigh those that could result from the reintroduction of their nuclear plants - by a factor of 263!  

Three Mile Island:

In March 1979 the almost new Three Mile Island unit 2 PWR was operating at almost full power when a minor malfunction in the secondary cooling circuit caused the automatic shut-down (taking about one second). A relief valve in the primary circuit however had failed to close but this did not show up at the control panel monitor nor was there provision in the control room indicating its position. The result was part of the primary coolant (water) drained off without the operator knowing, causing overheating and severe damage to the fuel rods. Subsequently there were a small amount of gaseous radioisotopes released. Several independent investigations were carried out and the Pennsylvania Department of Public Health involving health checks on 30,000 people over 18 years. No evidence was found of radioactivity induced illnesses or casualties and the average dose received was equivalent to a chest X-ray.

Cold shut-down conditions took a month to be established and the reactor was eventually decommissioned. Inadequate emergency response training and deficient control room instrumentation were found to be the main causes of the mishap. The most significant impact of the event was caused by misinformation spread by the media and state and federal officials which caused panic and mass evacuations.  

Chernobyl:

By far the worst of the world’s three nuclear accidents was Chernobyl Unit 4 which occurred on 26th April 1986 in the Ukraine. It occurred at one of the four Soviet design RBMK-1000 reactors at the site. In terms of the radiation that was released it was 10 times worse than Fukushima and 2 million times worse than Three Mile Island. Depending on which reference one chooses to believe death rates that will be attributed to the Chernobyl disaster range from a 4000 to almost one million. Some claims support particular anti-nuclear sentiment and open access to the then USSR documentation has been less that helpful. UNSCEAR and the World health Organisation (WHO) in their peer reviewed reports put the numbers somewhere in the region of 60 immediate deaths and 4,000 that likely resulted experienced thyroid cancer as a result of the leakage. Once again panic and stress due to ill-informed reports or the lack of official reports has created much inappropriate stress within the surrounding community. Other than these casualties UNSCEAR advice was that there was little risk to the 5 million people in surrounding Ukraine, Russia and Belarus. 

The RBMK-1000 was in effect a boiling water reactor but unlike other BWRs designed in the USA that use water jointly as a coolant and moderator, this design also had a graphite moderator. Under particular operating conditions it displayed what was known as a ‘positive void coefficient’; that is, bubbles forming in the boiling coolant could enhance the reactivity of the core rather than decrease it.

The incident has been attributed to plant operators illegally disabling safety interlocks which would safely shut down the number 4 unit automatically in the event of an incident. Their idea was to test how long the turbines would spin and continue to supply power to the circulating pumps following the loss of the main power supply. A similar test had been done the year previously indicating
changes were needed to the voltage regulator and this test was designed to check out results of their modifications. Apart from the fact there was no secondary containment building to isolate any radioactive discharge, this particular design had another key design fault, namely a positive void coefficient.

A series of actions prior to the test caused a surge in power and the reactor became unstable before the operator could safely shut it down. There was an explosion due to rapid steam build-up which partially dislodged the heavy vessel top plate and damaging core coolant circuits. As a result fission products were discharged directly to the atmosphere. A second explosion just a few seconds later, thought to be due to hydrogen from dissociated cooling water and zirconium from the fuel cladding, caused more discharge including large sections of the graphite moderator. This in turn caused the graphite to catch fire and releasing further radioactive fission products. In the following week some 5,000 tonnes of boron, sand clay and lead were dropped into the damaged vessel by helicopter in an attempt to stop the release.

Unit 4 was completely destroyed and is now completely enclosed in a concrete shelter with yet a larger one being prepared to be placed over the top again. After considerable design changes and expense the other 3 operating units were were systematically shut down between 1991 and 2000.

A list of accidental nuclear fatalities including those from research, weapons development, radiotherapy, the military and industrial radioisotope uses is included in Appendix 11. Where there were conflicting, but credible reports, we have tended to use the higher of the figures. A comparison with some other human endeavours is also provided. Nuclear fission safety records, while far from satisfactory, outperform those of most other activities.

11.4 Summary

The LCOE for nuclear fission varies with the discount rate used in the analysis (or effectively the cost of money). At 3% pa and 10% pa discount rate nuclear energy LCOE is deemed to cost around US$55/MWh and US$115/Mwh, - lower than large PV and offshore wind plants. At 3% pa nuclear LCOE is lower than coal and NGCC plants

Pros

- Nuclear industry is well established and reactors have accumulated 15,000 years of operation.
- While they have a GHG footprint due to construction, operational services and decommissioning, they otherwise do not emit GHGs
- Fission reactors have high capacity factors, regularly between 80% and 90%.
- Uranium resources are considerable and Australia has the largest share
- The EROI of PWRs and BWRs are lower than most other electrical generating units according to Argonne National Laboratory using GREET.
- Very low fatality rate per TWh compared to most other electrical generating units (see Appendix 11)
- They are high capital cost items but with comparably low lifetime costs.

**Cons**

- They have an immense public image problem to overcome in regard to acceptance following major accidents and graphic images in the media of the Fukushima nuclear accident in 2011

- They produce quantities of highly toxic waste some (about 3%) that has to be stored indefinitely

- At end of life nuclear plants need to be left standing for decades while radioisotopes decay enough to allow demolition and reduction of decommissioning costs

- There is sometimes an extreme and irrational perspective of anything nuclear adopted by some political parties, NGOs and individuals, quite possibly, much to our peril

- Access to cooling water in an ear of rising sea levels may require more use of hyperbolic cooling towers, a vision which does not appeal too much of the public

- Problems have been experienced with a number of old reactors in the UK and USA still yet to be decommissioned many years after they have stopped supplying power. Part of the problem is people on spent fuel transport paths not wanting the nuclear waste to be transported through their areas out of fear of accidents.
'If Congress doesn't understand, they won't fix the problem in time, and they certainly won't fix it if they think the voters don't care.' – William W Flint - 23rd June 2014

12 Nuclear Fusion

The pursuit of a virtually inexhaustible, low cost energy supply, available 24 hours a day, 365 days a year, free of nation-state fuel monopolies and harmful by-products, has been a long-term goal of many nations. Public announcements made in the 1950s hailed fission as such a holy grail of energy without much being said about its inevitable downsides of potential meltdowns, nuclear proliferation or fission products with their lengthy radiation half-lives.

Well the promise of nuclear fusion, if ever we succeed in harnessing it commercially, again brings this dream of clean, inexhaustible energy. The fuel used is reasonably available and comparatively very safe. The fusion products are largely inert and any radioactivity is largely constrained to the fusion reactor components and consumable themselves. The process is demonstrated continually in nature by the sun and stars. It represents a possible Holy Grail of energy supply for the 21st Century, but unfortunately time is not on our side.

Fusion is the antithesis of nuclear fission. Rather than breaking down some of the largest elements fusion incorporates the transformation of the lighter elements, such as hydrogen into larger ones (see Fig 12.1). As with fission there is a loss of mass involved in the process of producing energy (via Einstein's equation $E=mc^2$) but once again huge amounts of energy can be gained with only a small amount of fuel. In fission we are dealing with the penetration of low energy neutrons, which have no electrical charge, into a relatively large fissile nucleus. In contrast a fusion process requires the collision and adhesion of small nuclei containing positively charged protons (which strongly repel each other). This necessitates the overpowering of the inherent repulsive electrostatic (Coulomb) force. A formidable challenge for mankind despite the fact that nature continuously demonstrates its ability to do so with the profusion of stars that fill the night sky.
12.1 Triple product

There are many possible fusion reactions already demonstrated in the stars but comparatively few accessible to current technology on earth. The three basic requirements for a fusion reaction to take place are temperature \( T \) in °K (i.e. degrees Kelvin = °C + 273), density \( n \) (i.e. in nuclei per \( m^3 \))\(^v\) and confinement time \( \tau \) (the Greek letter tau measured in seconds). In combination they form what is known as the triple product \( n \tau T \). It usually has dimensions keV.seconds/nuclei per cubic metre or simply keV.sec/\( m^3 \) and is referred to as the Lawson Criterion (although confusingly sometimes this

\(^v\) Of note some fusion reports quote \( n \) as a mass density (g/cc) rather than particle density (nuclei/cc) which can be confusing but we shall endeavour to quote conversions whenever this is mentioned.
name is attributed to just the nτ portion). It was named after the engineer John D Lawson who originally defined it in 1955 but now contains slight modifications for certain gains and losses. Its minimum value required to achieve fusion is \(3 \times 10^{21} \text{ keV.sec/m}^3\) which is required for the easiest fusion reaction - Deuterium and Tritium (D-T or \(^2\text{H} - ^3\text{H}\)). This amount implies the need for extremely high temperatures.

Basically Lawson's criterion implies that in order for fusion of two nuclei to take place they need to be brought close enough to overcome the considerable repulsive forces between their respective protons and to stay in each other’s vicinity long enough to fuse. This means they will need to have considerable kinetic energy (viz. temperature), close proximity (viz. density) and dwell time. This criterion highlights the much greater challenge of fusion and consequently the energy density of fusion reactors will inherently be larger than fission reactors, implying higher capital costs per MWe with greater complexity.

The required value of the triple product for a specific fusion reaction can be met by various combinations of the individual values of \(n\), \(\tau\) and \(T\). If the density is high, such as in the immense gravitational forces in the sun, then dwell time and temperature need not be great. However, in attempting to replicate a fusion reaction on earth it is temperature alone that determines whether or not the Coulomb barrier will be breached (see Appendix 12 for more detail on the Coulomb Barrier).

An increase in temperature means an increase in particle velocity and therefore the kinetic energy of nuclei, which increases the chance of two nuclei approaching close enough to fuse (<10^{-15} metres or one Fermi). This basically requires temperatures to be so high that all orbiting electrons are completely stripped from the fuel atoms to form what is called a plasma – the fourth state of matter after solid, liquid and gas.

There is a fine balance to the optimum densities and temperatures in controlling a fusion reaction. If either are too high much of the energy generated is discharged as X-rays and gamma rays, known as bremsstrahlung: a German word meaning breaking (slowing down) radiation. This phenomenon results from an increase in the probability of nuclei slowing down due to interaction with each other or with electrons causing scattering and cooling of the plasma before fusion can take place. Bremsstrahlung presents a major challenge for harnessing fusion and must somehow be minimised and or converted to useful energy to reduce losses (Fig. 12.2).

**12.2 Cross sections**

Similar to its use in fission the ‘cross section’ unit is a measure of probability of a fusion reaction in regard to the relative velocity of the two nuclei, and is usually denoted as the Greek letter sigma \(\sigma\). The greater the value of \(\sigma\) the more likely that fusion can take place. It is itself a function of velocity and, as this varies over a wide spectrum of fusion reactions, an average is adopted, denoted as <\(\sigma_v\)> and termed the reactivity (with units of \(\text{m}^3/\text{sec}\)).

While fission particle energy cross sections can vary between 0.002 eV to 10 keV for thermal fission and 0.1 to 1.5 MeV for fast fission those of fusion light elements range from 10 keV to 1.0 MeV. So, while a fission reaction can effectively take place at room temperature, a fusion reaction needs an extremely high temperature and so it only in a plasma environment that fusion can take
As shown in Figure 12.2 the triple product for the D-T (21H – 31H) reaction must exceed $3 \times 10^{21}$ keV.sec/m³. When this value is exceeded there will be excess power output by the reaction. This can be satisfied by having $T=10\text{keV}$, $\tau=3 \text{ seconds}$ and $n=10^{20} \text{nuclei/m}^3$ as shown in purple.

There is therefore a range of the variables density, time and temperature at our disposal and this factor is the basis for having several paths of research as to how best to achieve ignition and beyond. One current path of research aims at relatively low densities and high temperatures while another high densities and lower duration times.

One of each type of research strategy is discussed in Appendix X.

![Figure 12.2 Conditions of the triple product for the D-T reaction. Adaptation from reaction curve presented in J Wesson et al Tokamaks 2004 paper. Courtesy: Wikimedia Commons - Drtrozzi](image)

### 12.3 Breakeven, Ignition and Q

The term ignition in a fusion reaction is analogous to its use when burning fuels in a chemical reaction such as a fire. The heat source, such as a burning match, can be removed once enough heat is generated by the fuel to burn unaided. This ignition condition in a fusion reaction occurs when the fusion process becomes self-sustaining and any external energy can be withdrawn. This happens when the fusion kinetic energy of the particles can be absorbed by the plasma providing the necessary heat source by to generate repeated collisions within the plasma. The external source of heat can be adjusted to maintain fusion at the required level and can be removed entirely if necessary so that the fusion reaction will quickly shut down (scram). It is for this reason that nuclear fusion is inherently safe from the problems associated with a loss of external power, which created problems during the Fukushima fission plant disaster.
A key requirement for a fusion reaction to be a viable source of energy is that the fusion power produced needs exceeds the external power applied.

We have yet to reach this condition.\textsuperscript{145}

Neutrons carry away the major part of the energy in the D-T reaction (Fig 12.3) as they have no charge and thus are unimpeded by the magnetic barriers used in nuclear reactors to contain the plasma. Their energy is captured as heat following a series of collisions with surrounding blankets and coolant circuits. This heat in turn could be harnessed to generate electricity in some conventional manner.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig12.3.png}
\caption{Comparison of triple product variable for three possible fusion regimes. Courtesy: Dstrozzi -Wikimedia Commons}
\end{figure}

12.4 Our sun

The primary fusion chain in our sun is that which occurs between hydrogen nuclei, as shown in Fig. 12.4 \textsuperscript{146} Larger, older stars can also 'burn' larger nuclei such as those of nitrogen, oxygen and carbon.
So why don't we just try to imitate what happens on the sun? Well there are two reasons:
1. The reaction time of the proton-proton fusion is extremely long.
2. There are other fusion reactions within our reach with higher energy release per fusion reaction, albeit at incredibly high temperatures ranging from tens of millions to billions of degrees.

Quite remarkably we have already exceeded the lower temperatures and are well advanced on those above a billion. Whereas the temperature at the centre of our sun is only 15 million °K.

The nuclei of the most common isotope of hydrogen (\(^{1}\)H sometimes referred to as protium) are strictly protons without any accompanying neutrons.
1. These protons fuse to form a deuteron and emit a positron (or positive equivalent of an electron) and a neutrino (virtually a particle of no mass or charge). The lost positron causes one proton to become a neutron thus creating the deuteron of one proton and one neutron. \(\text{Timespan (solar) of } 10^9 \text{ years}\) and accounting for 99% of the sun's energy.
2. Another proton fuses with a deuteron to form an isotope of helium nucleus (\(^{3}\)He nuclei) and emitting a gamma ray. \(\text{Timespan 1 second}\)
3. These helium nuclei then fuse to form a \(^{4}\)He nuclei and two protons. \(\text{Timespan (solar) } 10^6 \text{ years}\)

The energy released per fusion event is around \(6.7 \times 10^{-14}\) Joules or 0.418 MeV.

Reactions of most interest to us are those which preserve the total number of nucleons before and after fusion (i.e. rather than X-rays, gamma rays, and sub atomic particles such as positrons or neutrinos). As can be seen from Fig. 12.4, in stage 1 of the sun's fusion chain there are 2 nucleons (protons \(^{1}\)H) converted to one deuteron (\(^{2}\)H) with sub atomic particles accounting for other mass loss. The fusion reaction most prominently pursued for our energy generation is the D-T (deuterium \(^{2}\)H + tritium \(^{3}\)H) reaction; i.e. the 2 protons plus 3 neutrons accounting is maintained:

\[
^{2}\text{H} + ^{3}\text{H} \rightarrow ^{4}\text{He} + ^{1}\text{n} + 17.6 \text{ MeV}
\]

As you may note from Fig. 12.4 the initial link in the solar fusion chain is the H-H reaction (sometimes depicted as p-p, \(^{1}\)H-\(^{1}\)H, or even protium-protium). It produces only around 0.418 MeV, although further reactions down the solar fusion chain produce considerably more. The D-T reaction emits over 40 times \((17.6/0.418 = 42.1)\) more energy than that of an H-H reaction. To get some feel of the massive potential resource of D-T fusion energy, one kilogram has the potential to release 93.8 million kWh of fusion energy. So one kg of fused D-T would have the equivalent heating value of over 13,000 tonnes of Australian (25.46MJ/kg net bituminous - thermal) coal!
Deuterium and tritium (both isotopes of hydrogen) can be made to fuse to form helium (inert and not radioactive) plus a neutron. Tritium is not found naturally on earth to any extent and is a radioactive beta emitter with a half-life of 12.3 years which decays to inert helium $^3\text{He}$. It can be manufactured by neutron absorption by a lithium atom ($^6\text{Li} + ^1\text{n} \rightarrow ^4\text{He} + ^1\text{H} + 4.8 \text{ MeV}$ and $^7\text{Li} + ^1\text{n} \rightarrow ^2\text{He} + ^1\text{H} + 3\text{ MeV} - 2.5 \text{ MeV}$). The latter reaction is endothermic and hence absorbs some of the fusion energy but as $^7\text{Li}$ represents 93% of the isotopic concentration of lithium it is the major supplier of tritium of the two and the neutron produced may then interact with another lithium nuclei. Tritium is also formed due to deuterium absorbing a neutron in heavy water moderated and cooled fission reactors. Once fusion is achieved in a fusion reactor the neutron released would largely absorbed in an integral lithium blanket transferring heat in much the same fashion as a fast breeder fission reactor produces plutonium in a depleted uranium blanket or $^{233}\text{U}$ in a thorium blanket. Tritium can later extracted from the blanket by a salt extraction process to be used to make new fuel.

Fig. 12.5 The most easily achievable controlled fusion D-T reaction Source: Wikipedia Commons

In order to overcome the Coulomb barrier threshold temperatures in the order of $4.5 \times 10^7 \text{oK}$ are required for a D-T reaction and $40 \times 10^7 \text{oK}$ for D-D.

The Coulomb force repels like charged particles such as protons over a distance at a rate inversely proportional to the distance between them. While it has no impact on the neutrons the strong nuclear force has influence on both protons and neutrons. If the kinetic energy of the charged nuclei is sufficient when it approaches another it may overcome the Coulomb force and proceed within a distance of approximately 1 to 2 Fermi. Providing it can remain within that distance for long enough then fusion may take place. However as the plasma nuclei have an energy distribution (Maxwellian) those at the high tail end can overcome the Coulomb force while the mean plasma temperature is much lower. There is also a quantum mechanics phenomena involved allowing some nuclei to tunnel their way through.

Fig. 12.6 Interaction of the Coulomb and strong nuclear forces within one diameter of a nuclei.
12.5 Possible deuterium fusion reactions

There are four reactions that could take place involving deuterium. They can combine in what is known as the deuterium cycle.

<table>
<thead>
<tr>
<th>No.</th>
<th>Fusion reaction</th>
<th>MeV yield</th>
<th>MeV yield total</th>
<th>keV input threshold</th>
<th>Temperature threshold deg K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$^2_1H + ^2_1H \rightarrow ^3_2He + ^1_0n$</td>
<td>1.0 ($^3_2He$)</td>
<td>2.4 ($^1_0n$)</td>
<td>3.4</td>
<td>400 million</td>
</tr>
<tr>
<td>2</td>
<td>$^2_1H + ^2_1H \rightarrow ^3_1H + ^1_1H$</td>
<td>1.0 ($^3_1H$)</td>
<td>3.0 ($^1_1H$)</td>
<td>4.0</td>
<td>400 million</td>
</tr>
<tr>
<td>3</td>
<td>$^2_1H + ^3_1H \rightarrow ^4_2He + ^1_0n$</td>
<td>3.5 ($^4_2He$)</td>
<td>14.1 ($^1_0n$)</td>
<td>17.6</td>
<td>45 million</td>
</tr>
<tr>
<td>4</td>
<td>$^2_1H + ^3_2He \rightarrow ^4_2He + ^1_1H$</td>
<td>3.7 ($^4_2He$)</td>
<td>14.7 ($^1_1H$)</td>
<td>18.3</td>
<td>350 million</td>
</tr>
</tbody>
</table>

Table 12.1 Possible deuterium reactions. It becomes obvious as to why the D-T reaction target presented most promise\textsuperscript{148}. Combined table from ref cx1 and cx1iii

The lower threshold temperature of the D-T reaction i.e. a minimum temperature at which fusion ignition may take place, plus the high energy yield makes this appear to be the most achievable. In fact, fusion of this form has been demonstrated in several reactors, such as the Joint European Test (JET) facility located in the UK, and the JT60U facility in Japan. While Breakeven has yet to be achieved, controlled fusion (as opposed to the uncontrolled fusion in a hydrogen bomb) reactions involving D-T have been demonstrated since 1991.

It can be seen from reactions 1 and 3 of Table 12.1 that while neutrons are generated from key D-D and D-T reactions they are not essential to propagate fusion (as in a fission reaction) Also, their physical nature does present a downside in as much as they can be inadvertently absorbed by reactor components causing them to become radioactive. While not as severe as those in fission product waste they nonetheless radioactive and present an operator health hazard. If somehow neutron generation could be minimised then this would be a major attraction of this alternative energy source.

There are also other fusion reactions that do generate reduced neutrons in quantity. These are termed aneutronic reactions, and to qualify as such, any neutrons released must not contribute more than 1% of fusion energy. Some of these reactions are discussed below.

12.6 Aneutronic Fusion

Aneutronic fusion reactions involve larger nuclei i.e. those possessing more than two protons. These reactions require even higher threshold temperatures as the Coulomb force increases with the larger nuclei and ignition temperatures can exceed 1 billion deg K. Again this temperature target has been achieved in practice.
Table 12.2: Some of the possible aneutronic fusion reactions

<table>
<thead>
<tr>
<th>Fusion reaction</th>
<th>Yield Gwh_{fusion/kg}</th>
</tr>
</thead>
<tbody>
<tr>
<td>A $^{1}<em>{1}\text{H} + ^{11}</em>{3}\text{B} \rightarrow ^{3}_{2}\text{He} + 8.7\text{MeV}$</td>
<td>19.4</td>
</tr>
<tr>
<td>B $^{1}<em>{1}\text{H} + ^{6}</em>{3}\text{Li} \rightarrow ^{3}<em>{2}\text{He} + ^{4}</em>{2}\text{He} + (1.7 + 2.3)\text{MeV}$</td>
<td>15.3</td>
</tr>
<tr>
<td>C $^{1}<em>{1}\text{H} + ^{7}</em>{3}\text{Li} \rightarrow 2^{4}_{2}\text{He} + 17.2 \text{MeV}$</td>
<td>57.5</td>
</tr>
<tr>
<td>D $^{3}<em>{2}\text{He} + ^{6}</em>{3}\text{Li} \rightarrow ^{1}<em>{1}\text{H} + 2^{4}</em>{2}\text{He} + (16.9 + 1.9)\text{MeV}$</td>
<td>55.8</td>
</tr>
<tr>
<td>E $^{3}<em>{2}\text{He} + ^{6}</em>{3}\text{Li} \rightarrow ^{2}<em>{1}\text{H} + ^{7}</em>{4}\text{Be} + 0.113\text{MeV}$</td>
<td>0.335</td>
</tr>
<tr>
<td>F $^{3}<em>{2}\text{He} + ^{2}</em>{1}\text{H} \rightarrow ^{4}<em>{2}\text{He} + ^{1}</em>{1}\text{H} + 18.3\text{MeV}$</td>
<td>97.5</td>
</tr>
<tr>
<td>G $^{3}<em>{2}\text{He} + ^{3}</em>{2}\text{He} \rightarrow 2^{1}<em>{1}\text{H} + ^{4}</em>{2}\text{He} + (8.6 + 4.3)\text{MeV}$</td>
<td>57.3</td>
</tr>
</tbody>
</table>

Note. These are all regarded as aneutronic fusion reactions as they do not precipitate a neutron. Item F is also listed as the fourth of the deuterium chain reactions above (4 of Table 12.1). If commercially achievable aneutronic fusion would present a bonus in that incidental radioactivity of the reactor structure is far less likely to occur. The larger the number of protons in respective nuclei the greater the temperature required to overcome the Coulomb force and hence the degree of difficulty. As will be seen from Fig 12.1 natural helium is almost 100% $^{4}_{2}\text{He}$ and availability and required separation of $^{3}_{2}\text{He}$ makes it possibly an unattractive choice of fuel despite the high fusion energy yields. So reactions A & C seem to be the most practical of any.

12.7 Increasing challenges

A comparison of the ease, or rather difficulty of obtaining a fusion reaction of one form or another is illustrated in Fig. 12.7

The ITER D-T project is likely to operate at a temperature of around 150 million $^\circ\text{K}$. This is considered the so called Goldilocks temperature which optimises dwell time at minimum Bremsstrahlung, those heat stealing X-rays. This equates to approx. 12.9 keV. In contrast aneutronic p-B11 is likely to have to operate at 200 keV or 2.32 billion $^\circ\text{K}$ or even higher. This may sound a staggering challenge but a temperature of 2 billion $^\circ\text{K}$ has already been achieved in 2006 in New Mexico by Sandia’s Z pinch inertial fusion facility.

Fig 12.7 Comparison of some reaction thresholds, Courtesy University of Washington
12.8 D-T fusion

The pursuit of a sustainable D-T reaction has been in progress for more than 60 years. Other than in a hydrogen bomb, which requires the massive impact of a supercritical fission reaction, a controlled fusion process is yet to be demonstrated as a viable energy source on earth. In recent years however the quest to reach the required triple product has advanced at a significant pace and progress has actually outpaced the so called Moore's Law of technological progression.\textsuperscript{vi}

Currently there are two major approaches to D-T fusion research. Magnetic Confinement Fusion and Inertial Confinement Fusion. Much of the early fusion research was done in the former USSR on so called magnetic confinement of the D-T plasma. As the required temperatures are incredibly high no solid containment is practical. Instead the plasma is corralled in a magnetic 'bottle' which the Soviets called a Tokamak. The name was derived from the Russian words to describe a torus shaped magnetic chamber.

The magnetic confinement takes advantage of the inherent electrostatic charge on the hydrogen isotope nuclei that is stripped of all electrons. It is no mean feat to contain plasma, as one can imagine. A vacuum is first created in the reactor vessel. Massive superconducting coils are employed to maintain the required magnetic flux. Both nuclei and electrons follow the magnetic field lines but in opposite directions at densities much lower than the atmosphere and at the extremely high temperatures required for them to fuse.

Tokamak:

The concept with which we have most experience is the Tokamak, the schematic layout of which is presented in Fig.12.8. In 1997 the EUROfusion's Tokamak called JET based in Culham UK, managed to reach 70\% of the D-T breakeven conditions (24 MWs of power in, for 16MWs of power out) albeit for a very short period. There are plans to break this record during tests in 2017 & 2018\textsuperscript{152}. JET has been operating since 1983 and in 1991 was the first reactor in the world to reach fusion conditions using D-T fuel.

\textsuperscript{vi} Moore's Law describes the doubling time of the number of transistors produced on a single chip. Gordon Moore was a co-founder of Intel and coined the concept in 1965.
The above simplified diagram illustrates the resulting plasma circulation.

Fig 12.8 Simplified schematic of the primary magnetic fields causing the plasma to rotate well clear of the reactor walls in a helical fashion. Courtesy: Michael Capewell

The notion of the magnetic coils in a Tokomak is to prevent the plasma from contacting the reactor walls and causing damage and plasma cooling. To achieve this two magnetic fields with their axes at right angles interact to create a heated, spiralling plasma.

The poloidal (ohmic) heating has to be supplemented since we are talking currents comprising millions of Amps and the transformer primary, subject to a gradual build-up of current, has its limitations. Also as the plasma heats up in this fashion the required resistance decreases and it becomes less effective and heating is limited to somewhere around 20 to 30 million °K (high maybe than the core of the sun but not high enough for us). The constraints on the transformer primary also necessitates intermittent (pulsed) fusion rather than continuous. The pulse length could last longer but the primary task of ITER is to reach Q \approx 10 in an approximately 500 seconds pulse although experiments are most likely to take place to find ways of extending this and pulse time and its frequency of operation.
The additional outer poloidal coils help trim the plasma and away from the reactor walls. The Divertor is where the any unwanted plasma, impurities and waste (Helium ash) is removed. It is exposed to extreme power loading and hence very vulnerable to damage and wear. Ways to spread this are being undertaken at Culham by initiating turbulence in the plasma.  

Note: The reactor however is far more complex than as shown above as can be seen by the cutaway of ITER Fig. 12.10

Hence to reach the 100 to 200 million degrees K additional forms of heating are applied. These consist of:

- Neutral Beam Injection heating which involves first accelerating such as deuterium ions via a magnetic field then recombining same with their electrons just prior to injection into the plasma thereby producing neutral atoms while maintaining their high velocity. Whilst in the plasma they are again stripped of their electrons while imparting their kinetic energy to the plasma in repeated collisions.

- Radio frequency heating involving the generation of high frequency waves by oscillators such that the energy can be transferred to plasma nuclei, thereby increasing their velocity and causing them to collide with others and generating heat.
- Ion and electron cyclotron injection devices to again project energy into the plasma.

In order to take JET experience to the next level Europe, Russia, Japan and USA formed a consortium under the International Atomic Energy Agency (IAEA) in 1992 to prove fusion as a viable future energy source. Since that time China, Canada and Kazakhstan have also joined the group. The notion was to build a much larger Tokamak than JET to increase the torus volume to periphery ratio in order to reach a power in to out ratio (Q) of 10. The planned new reactor is called ITER, an acronym for International Thermonuclear Energy Reactor. A design was drawn up between 1988 and 1990 and after much 'discourse' it was agreed to build ITER in Cadarache in southern France. Construction has been under way since that date and the schedule for demonstrated fusion is 2033.

The main criteria for ITER includes:

1. 'achieve extended burn in inductively driven plasma (read poloidal ohmic heating as per above) with a ratio of fusion power to auxiliary heating power of at least 10 for a range of operating scenarios and with a duration sufficient to achieve stationary conditions on the timescales characteristic of plasma processes.
2. aim at demonstrating steady-state operation using non-inductive current drive with a ratio of fusion power to input power for current drive of at least 5'

It should be noted that ITER will not generate electricity. Instead the fusion energy generated by the neutrons will be converted to heat in a water heat exchanger system designed also to extract any tritium. The heat will be likely used for local heating or simply dumped. ITER will remain another test facility in order to demonstrate controlled fusion and provide design concepts for a later power plant prototype to be called DEMO of much higher fusion gain (Q = 30) and 2000MW fusion power possibly with a larger radius, some decades later. Initially ITER will not generate its own tritium but rely on external sources such as from the nuclear fission industry in Canada. It will be considerably larger than the largest existing Tokamak (JET) which has a major torus radius of 3.1m while that of ITER will be 6.2m. It will also support a plasma current of 15MA (15 million Amps) compared with JET's 6 MA and with much stronger magnetic fields. It will also use super-conductive magnets (see Appendix 10) to reduce input energy losses.

ITER will have an input (auxiliary) power supply of 50MW and be expected to demonstrate a fusion power of 500MW (i.e. Q =10) for a burn length of 400 seconds. The burn length is determined by how much strain can be imposed on the transformer which provides some of the auxiliary heating energy and contributes to the poloidal magnetic containments. Just how soon it can be re-energised does not seem apparent in the literature but clearly from the design parameter above transformer fatigue may be an issue.

As the main criteria above indicates once ignition is shown to be readily achievable then a Q = 10 is to be pursued.
The ITER reactor vessel is approximately 35m in diameter and in height. There will be a surrounding building housing overhead cranes, fuelling machine and external plasma heating, cryogenic systems for the superconducting magnets and cooling water feed systems to make up what would be normally regarded in a fission plant as the nuclear island or steam supply (see Fig. 12.11). Note the man shown bottom right which gives an idea of scale.

**Fig. 12.10** Cutaway of ITER reactor vessel. Courtesy: ITER

Fuel is likely to be D-T gas on start-up followed by frozen D-T while operating and in excess to help increase the density. It has also been discovered that tritium can be deposited in cooler sections of the vessel forming hydrocarbons. After one operating campaign nearly 18% of tritium fuel consumed was lost in this way.

Nonetheless fuel cost will be very much a secondary concern to capital, operating and maintenance costs for fusion in general. For the D-T reaction a 1 GWe fusion plant will only need about 100kg of deuterium and 3 tons of lithium per year. 155
The overall 500MWt ITER virtual steam supply system appears will be approximately 70m in length and also in height. While this is strictly a test facility that will provide better design data for the commercial prototype design DEMO, compared to the steam supply of a 2500MWt light water (fission) reactor, Fig. 12.12, it is enormous and Tokamaks may reflect negatively in a commercial plant cost comparison in the same way as the Advanced Gas Cooled (fission) Reactor (AGR) only more so.

Fig 12.11: The cross section of the ITER heat supply plant. Courtesy: ITER

In contrast the steam supply overall dimensions of a much larger pressurised water reactor and particularly a fossil fuel fired gas turbine is shown in Fig. 12.12
In contrast to the 500 MWt ITER a 2500 MWt light water nuclear steam supply envelop is approximately to scale at 45m diameter and 70 m high. An advanced gas turbine of 840MWt profile is also shown for comparison. As cost is related to footprints it is easy to see which source the power utilities would be pushing for.

Fig. 12.12 Profiles of light water reactors and a current fossil fuel gas turbine to the same scale as the 500 MWt ITER of Fig. 12.11

In July 2014 the scientific periodical *Nature* included an article on ITER's progress.\(^{156}\) It reports that the seven nation project's cost has risen approximately 10 fold over the original budget to US$50 billion and the schedule for initial fusion has blown out to 2027 instead of 2016. Even if the original timeline is adhered to from then in it will be another 5 or 6 years before the Q=10 target is reached.

The main criteria design remit above provides for a fusion power gain Q of 10 albeit for just over 8 minutes. Hopefully the pulse time can be extended and its repetition cycle minimised without imposing the central transformer from risk of fatigue. Then the 50MW of alpha power is required to provide \(10 \times 50 = 500\) MW of fusion power. Assuming this fusion power can be completely converted to heat power (100% efficiency) and that the heat power can be converted by to electricity at 45% (with a gas turbine or other) then 50MW of the recycled alpha fusion power translates to \(450 \times 45\% = 202.5\) MW. Take away plant self-consumption of power (for superconductor cryostat pumps, water cooling pumps, fuel handling, lighting etc.) of say 25 MW that the overall net electrical export would effectively be \(202.5 - 25 = 177.5\) MW. A summary of this calculation is given in Appendix 12

In summary it is highly likely ITER, if completed will demonstrate a Q value greater than 1 but it is hard to imagine this very complex Tokamak option ever becoming a commercial reality. Even more certain is that Tokamaks will not be ready in time to contribute to the de-carbonising the global energy systems by 2050.
Inertial Confinement Fusion (IFC):

A totally different approach to D-T fusion has been under-way in the USA. The so called National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in California gained approval in 1993. Construction started in 1997 but it was not completed until 2009 at a cost of US$5 billion. It is a joint venture project between the National Nuclear Security Administration (NNSA) as part of its nuclear weapons arsenal security or Stockpile Stewardship Security program (SSP) and the US Department of Energy.

NIF uses an inertial confinement process by way of extremely powerful lasers which convert their light into X-rays in order to impose an immense amount of energy for just a few billionths of a second on a small approximately 2mm diameter spherical pellet containing D-T fuel. It thereby imposes a pressure of billions of atmospheres on the pellet compressing it to a fraction of its original volume. In doing so it increases the density (n) such that the pellet's mass density is often quoted as being dozens of times that of lead while increasing the temperature (T ≈ 100,000,000°K) of the fuel. LLNL are aiming for a pressure of 300 billion atmospheres.

The somewhat modest laser pulse initially generated in what is called the Master Oscillator Room is amplified trillions of times via energy implied from huge capacitor banks into flashes of light in the laser bay directed at slabs of glass embedded with the element Neodymium (14460Nd). This element gives off two photons for each one received from the flash lamps, creating the laser amplification. One hundred and ninety two of these laser beams spaced radially around a 10 metre diameter spherical vessel under vacuum, called a target chamber, are directed at what is termed a hohlraum (a German term for cavity). The hohlraum is a small cylindrical vessel slightly less than 10mm long and 6 mm diameter. It is made up mainly of gold or depleted uranium and possibly at some stage, lead. At its centre is placed the fuel pellet which has been frozen to near absolute zero.

When the laser pulses strike the inside walls of the hohlraum X-rays emerge which bombard the fuel pellet causing it to compress and, hopefully fusing the fuel. Again this is a pulse type operation and hopes are for the future the process can be repeated many times a second to provide a viable energy source, although its original design concept limited this to around 700 pulses per year.

What the lasers actually try to emulate is the immense pressure exerted on hydrogen isotopes by the triggering effect of the fission fuel in a thermonuclear weapon. The huge difference is the minute amounts of D-T fuel used in a NIF pellet (0.238mg or so) which puts a finite limit on any fusion
energy delivered per pulse.

An article in the Scientific American journal 2014\textsuperscript{161} provided results of a successful fusion experiment at NIF which was claimed to produce more energy from the fuel \textit{than it absorbed}. These three words are very significant since much of the external energy for inertial fusion is absorbed. The Scientific American report reveals that 500 MJ (139 kWh\textsubscript{e}) of electrical energy were used to produce the 0.17 MJ (0.0047 kWh\textsubscript{f}) of fusion energy. If we allow a generous conversion efficiency of the fusion energy to electricity of 45\% the fusion energy would, if the necessary turbine generator where provided, be converted to 0.0021 kWh\textsubscript{e}, or in other words a realistic Q \approx 0.000015.

While NIF must somehow be very beneficial in securing the US nuclear stockpile in some form or another, with limitations of only 1 or two pulses per day makes this facility purely scientific experiment with an extremely low EROI. As with ITER, the fusion, temperatures and pressures attained to date are engineering triumphs, but looking at the bigger picture it is hard to imagine NIF

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{nif]^*
\caption{An artist's depiction of NIF.}
\end{figure}
leading to a commercial fusion reactor at any time soon.

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**Stellarators:**

One disadvantage of the Tokamak is the irregular density of the plasma over its cross section being less dense on the outside than on the inside. The differential magnetic force allows some nuclei on the outside to 'wonder' out of the mainstream and hit the walls of the torus. By rearranging the toroidal magnets into a twisted configuration shown in Fig. 12.16 the resulting plasma is guided around the torus gradually cycling from inner to outer positions. While still presenting many challenges one major benefit of a Stellarator is that the Tokamak’s vulnerable transformer is not required and hence much longer or even continuous operation are at least feasible.

After much stop-start budget machinations Germany now has installed the largest of these extremely exacting machines at the Max Planck Institute in Greifswald and in late 2015 it underwent commissioning tests. It is much the same diameter torus as ITER and well in front of ITER's schedule. It is called Wendelstein 7-X or simply W7-X and costs to date are €1.06 billion, a great deal less than ITER. But according to the Institute's brochure it will not be used to generate energy and will be using a mixture of hydrogen (protium) and deuterium as the test 'fuel'.

There are approximately a dozen Stellarators operating experimentally around the globe. The previous largest (Large Heliotron Device LHD) has been operating in this manner in Japan since 1998.
A view of the W7-X designed using modern supercomputers to meet the degree of accuracy required of the very complex shapes. Also a schematic of the plasma flow

Fig. 12.16 W7-X under construction. Courtesy: Wikipedia Commons

**Lockheed-Martin – Compact Fusion Reactor (CFR):**

The giant engineering company Lockheed Martin announced back 15th October 2014 that it was developing what they term as a high beta fusion reactor and plan to have a commercial product within a decade. Amazingly Dr Thomas McGuire, the leader of the group handling the project,
advised various reporters that they anticipated their Compact Fusion Reactor (CFR) will be capable of generating 100MW of power, sufficient to supply 80,000 homes, and be in the order of only 7m (diameter) and 12.8 m long. It is not stated whether the 100MW is thermal or electrical energy but 100MW of electricity would be able to supply around 63,000 US homes and over 100,000 Australian homes at the present rate of annual consumption. However as the fuel will be D-T direct electrical conversion is unlikely, and it is difficult to imagine the space for a turbine generator in these dimensions.

The CFR has been termed a high beta reactor. Beta (β) has been regarded as the ratio of the plasma pressure to the confining magnetic pressure in magnetic confinement reactors. And fusion power is directly proportional to $\beta^2 B^4$ where $B$ is the magnetic field strength. Hence power will increase in proportion to the square of $\beta$ and if this ratio becomes much greater than 5% in Tokamak or Stellarator configurations then instabilities occur in the plasma. What the CFR team regard as their goal is a considerably higher Beta ratio (maybe as high as 100%) and hence power density due to their chosen magnetic confinement strategy.

Lockeed Martin's promotional website [http://www.lockheedmartin.com/us/products/compact-fusion.html](http://www.lockheedmartin.com/us/products/compact-fusion.html) suggests it could be used to replace conventional jet engines on aircraft. This would be a major advantage as synthetic jet fuel is likely to have a very poor EROI using current technology. Nonetheless it would be interesting to hear how they would address the shielding of passengers from stray neutrons.

Little else has been published to date on their revolutionary concept and while there is an abundance of scepticism about their claims in the media and prominent physicists we can only wish Lockheed Martin well in their development schedules.

**General Fusion:**

Yet another novel approach is to combine the two concepts of magnetic and inertial confinement in what is being termed Magnetised Target Fusion. General Fusion was set up in British Columbia, Canada in 2002. Instead of a forced magnetic fields to encapsulate the plasma General Fusion uses a phenomena of nature called a Compact Toroid (CT) and high speed hammers synchronised to generate high pressure acoustic pulses or shock waves in the plasma.

There are several ways of generating a CT but they all basically involve passing a series of sufficiently large currents along a plasma charged magnetic field in a predetermined sequence.

There are two basic types of CT, used in fusion experiments, one is a Field Reversal Configuration (FRC) and the other is called a spheromak. Both involve magnetic fields forming the shape of an elongated smoke ring that is stable from anywhere between nanoseconds to microseconds and during that time capable of constraining and compressing a plasma. The FRC displays only poloidal fields and need an external magnet array to maintain the confinement whereas the spheromak, has both inherent poloidal and toroidal magnetic fields. They both have their merits in regard to plasma confinement. The FRC exhibits better $\beta$ values and hence density and the spheromak demonstrates better confinement times ($\tau$) and temperatures ($T$). CTs are similar to astronomical phenomena as in plasmoids (mentioned later), fire balls and coronal loops. Inherently they can demonstrate both poloidal and toroidal magnetic fields such as those artificially generated in a Tokamak but with a CT these are self-generated by what is termed the
magnetic dynamo characteristics of the high temperature plasma nuclei and associated electrons.\textsuperscript{167}

General Fusion are researching the use of both CTs and their concept\textsuperscript{168} is to have a chamber which rotates a liquid of lead and lithium at high speed contained in a metal sphere about 3m in diameter. The rotation causes the pool of metal to hollow out into a vortex into which horizontally opposed CTs are fired entering the vortex from each end to collide and combine at the centre. Somewhat similar to the NIF laser set-up, some 200 or so synchronised pneumatic pistons surrounding the metal sphere hammer away at a rate of around 100 metres per second\textsuperscript{169} providing the necessary shock wave compression to heat and increase the density of the plasma before the combined CT disperses.

What the company describes as a CT accelerator employed to inject the fuel into the vortex appears to be some type of sophisticated coil gun (Fig. 12.17). The chosen fuel is again D-T and the fusion energy is to be transferred to heat energy in the liquid metal while also generating a source of tritium.

General Fusion are attracting a lot of publicity in the media and as of Oct 2015 they have raised $100 million and are running with a team of 65 staff. Like Lockheed they are aiming at a much smaller power plant package than Tokamaks or the NIF.

Fig. 12.17 A Compact Toroid magnetic ‘cage’ and Coil Gun. Courtesy: Wikimedia Commons
General Fusion’s target 1. Liquid metal spins to form a vortex 2. Opposed plasma injectors then fire in their CTs where they combine. 3. Pneumatic hammers at 100m/s repeatedly 4. Plasma in the CT fuses and energy converted to heat in the metal which is transferred to a steam cycle and hence a turbine generator.

Fig. 12.18 Schematic of General Fusion's experimental fusion reactor. Courtesy Wikimedia Commons – Evan Mason

**Pros (D-T fusion)**

D-T will most likely be the first fusion fuel successful in reaching breakthrough due to the relatively low triple product demands and present level of development on several fronts.

One of the two fusion products $^4\text{He}$ is both inert and stable. It is therefore an asset rather than a waste problem as helium is used in industry, diving gas, and a buoyancy gas for inflatables. Helium is currently found entrained in some natural gas (fossil fuel) streams. As we need to leave this fossil gas in place in future there is likely to be a good market for this fusion 'ash'.

Deuterium fuel does require extraction via the processing of considerable amounts of water but small amounts provide immense amounts of energy as illustrated earlier. The process is well established. Lithium too is reasonably abundant as a tritium source so fuel costs at least will be a minor part of plant operational costs.

**Cons (D-T fusion)**

With the possible exception of the success of the CFR proposed commercial plants will be massive in comparison to nuclear fission or current fossil fired plants and hence extremely expensive in comparison.

EROI will be quite unattractive unless Q values can somehow be increased to 50 or more without a comparable increase in plant size.

As the fusion products includes neutrons which also carry much of the fusion energy, there is the high probability of radioactive waste from stray neutrons in the form of reactor components and their replacements. The volume of radioactive waste should be much less than that of a comparable capacity fission reactor but an issue nonetheless. Maximum neutron capture, after they have
dispensed most of their inherent kinetic energy, must be a key factor in the lithium blankets in order to minimise this while also maximising the production of tritium fuel.

Tritium is itself radioactive and will combine with oxygen to form tritiated water (HTO) which will be a hazard if ingested by humans and mammals in general. Process plants to capture stray tritium would need to be provided at the power plant.

Many instabilities in the plasma need to be understood and harnessed

Operating superconducting magnets at close to absolute zero temperature in the close proximity of extreme plasma temperatures must present heat transfer challenges.

As the majority of fusion heat will be represented by the neutrons emitted (see Fig. 12.5) the option of direct conversion to electricity is not practical. Steam or gas turbines cycles with their limited inherent efficiencies will need to be used.

12.9 D-D reactions

As noted in Fig. 12.7 a D-D is the next less difficult reaction to aim for but this reaction can also produce a neutron and with far less fusion energy released than D-T. The main advantage over D-T would be that tritium is not required. So we will take a look at some of the aneutronic fusion research which although much harder to achieve has the real promise of:

- much less environmental impact i.e. no tritium,
- greatly reduced neutron emission,
- much smaller size than the equivalent Tokamak and
- much higher conversion efficiency to electrical energy.

12.10 Aneutronic Fusion

The most predominant fusion reaction for aneutronic fusion does not include neutrons as part of its fusion products. Other minor reactions may but overall neutrons must not generate more than 1% of the overall fusion energy from their neutrons to qualify the fuel as aneutronic. In the case of $^{1}_1\text{H} - ^{11}_5\text{B}$ (often referred to as p-B11) the major reaction is shown in Table 12.2 as having no neutron discharge. Occasionally there are different fusion products and sometimes reactions with fusion products from an earlier event and secondary equations for this fuel are:

$$^{1}_1\text{H} - ^{11}_5\text{B} \rightarrow ^{11}_6\text{C} + ^{1}_0\text{n} - 2.8\text{MeV}$$

and

$$^{1}_1\text{H} - ^{4}_2\text{He} \rightarrow ^{14}_7\text{N} + ^{1}_0\text{n} + 157\text{keV}$$

These are low yield (about 0.2% overall) but nonetheless precaution have to be taken by way of shielding, in the form of a water jacket and an efficient neutron absorber such as $^{10}_5\text{B}$, to protect operators.

Some of the challenges of this aneutronic strategy compared to the D-T road map include:
The Coulomb barrier increases with the number of protons in a nuclei and hence more external energy (temperature) is required for nuclei larger than hydrogen. Boron has 5 protons and hence the
threshold temperature has to be considerably higher to counteract the Coulomb barrier. In fact something like 13 times higher at 2.32 billion °K.

Some of the current aneutronic projects are discussed briefly below.

**Helion MTF:**

Helion Energy based in Washington State USA state that they are developing an aneutronic fusion reactor for D-He3 (\(^{1}\text{H} - ^{3}\text{He}\)) research which appears to be using a combination of two proven techniques. One is a coil gun they refer to as an Inductive Plasmoid Accelerator (IPA). The other is a CT or more precisely a Field Reversal Configuration (FRC) type CT.

Two such CTs are generated and fired at each other using two coil gun type accelerators\(^ {170}\) to form a single central cell where external magnetic forces are imposed to compress it further. the organisation’s website suggests they are aiming at fusion temperatures 'over 100 million degrees' although this may seems low for this fuel which would require extremely high densities and/or dwell times (as Fig 12.7 suggests). Helion's website http://www.helionenergy.com/ implies the process takes advantage of both inertial and magnetic confinement technologies and suggests a 50MW shipping container sized reactor again with direct electrical energy conversion.

Although Helion's website suggests the He3 (\(^{3}\text{He}\)) component of the fuel will be available from the reactor's exhaust this seems hard to comprehend as both fusion reactions involving He3 fuel to create only He4. So perhaps their greatest challenges may be obtaining the He3 fuel as it only forms a minute proportion (0.00137% as per Fig. 12.1) of a reasonably scarce helium reserves, mainly held by the US National Helium Reserve and according to some sources may expire within the next 25 to 30 years (especially if we continue to use it for inflating party balloons). The earth's crust contains about 8 parts per billion of helium so He3 is only 0.00137% of that. Tritium decays to He3 with a 12.33 half-life so it has been suggested that some may now be available from the nuclear fission industry, especially from reactors using heavy water moderator/coolant. Interestingly there is a large deposit embedded in the surface of the moon due to solar bombardment and at other solar system entities. But retrieving any of this will provide its own problems. They do seem to have a prototype in place but are yet to have released any results publicly. Also Princeton Satellite Systems Inc. in New Jersey are experimenting with D-H3 fuel as a potential space rocket fuel using a CT.\(^ {171}\)

Nonetheless the reactor concept seems promising and is one also being adopted as part of Canada's General Fusion developments\(^ {172}\) only with D-T reactions and Tri Alpha (below), who are planning to use p-B11 fuel.

**Polywell:**

A company called EMC2 in Santa Fe, California is developing what they call a Polywell. It adapts electrostatic properties to round up and impound fuel nuclei in a suspended cloud (or a well, hence the name Polywell) at the centre of their evacuated compact fusion unit they call a Magrid.

Over many years EMC2 has researched properties of two physical phenomena which they now exploit and combine to optimise their fusion reactor. These are 1) electrostatic fusion, where high energy electrons are injected generating the potential well, mentioned above, thereby confining and heating the ions (nuclei) to a plasma status once injected and 2) a high β cusp which confines
energetic electrons in a surrounding magnetic bottle or what they refer to as a wiffleball, to increase
the \( \beta \) value and hence the increase the density of the trapped plasma. The notion is that they will
work in tandem to enhance both D-T and p-B11 nuclear fusion.\(^{173}\)

These units will be quite compact as there is the optimum size of what is called their Magrid is 1.5m
radius. Fusion power output is proportional to the seventh power of the Magrid's radius (\( P = 5.85 \times R^7 \)) and Polywell state the strength of modern construction materials could not cope with anything
much larger than the optimum.

Unlike some other aneutronic projects Polywell has achieved actual fusion and in 2005 their
prototype WB-6 produced \( 10^9 \) fusions per second. They now have a WB-8 unit and feel confident
they can build a high \( \beta \), 1.1GW\textsubscript{fusion} 'test' unit requiring a heating power load of just 185MW 'within
a few years' albeit with D-T fuel. Their research however is aiming for p-B11 fusion.

![An impression of the core of EMC2's Polywell which would be contained within a vacuum vessel. The 3 sets of opposing magnets form what is termed a Magrid and their magnetic fields form a central 'pocket' for introduced electrons (vertical line) shot in from surrounding electron guns, keeping them clear of the Magrid which would otherwise cause loss of energy. As their density increases the magnetic lines of force generated by the magnets 'expand' outwards and form what is referred to as a negatively charged potential well at the same time restricting any electron escape routes. Next, solid fuel ion guns strip off and ground electrons from their hydrogen and boron charges and feed the ions (horizontal line) into the potential well where they accelerate due to the negative charge to such a degree they can collide and potentially fuse to form helium before they can be de-ionised.](image)

Fig. 12.19 a visual impression of Polywell's 'heart'. Courtesy: Polywell/Wordpress

**Dense Plasma Focus Fusion (DPF):**

Yet another approach to compact aneutronic fusion uses what is called a Plasma Gun. This device
was invented way back in 1954 in the Soviet Union by N V Fillipov and later independently by J W
Mather. A very basic sketch of a Plasma Gun is shown in Fig. 12.20. Again the unit is enclosed in a
vacuum chamber and fusion fuel is injected. The sketch shows the test gas to be hydrogen but more
currently it is likely to be argon for X-Ray studies, deuterium for fusion and neutron generation
purposes and p-B11 for aneutronic fusion experimentation. Much in the same fashion as a coil gun a
plasma sheath is propelled along the axis of the anode pushed along by the magnetic field into what
is called a pinch, which forms at the end of the cathode carrying the fuel charge with it. The
magnetic field is generated when the capacitor banks are allowed to discharge. At the end of the
anode the plasma sheath interacts with its own magnetic field causing it to collapse to a very dense
ball, called the focus, encapsulating and compressing the contra rotating filaments of the ionised
fuel. The focus can be described as plasmoid, a minute version of those referred to in astrophysical
studies, ball lightening etc. The focus is unstable and breaks up after a few nanoseconds, in a small
unit, and to a microsecond in larger units. The outcome is a burst of radiation in the form of X-rays
(Bremsstrahlung) and, if fusion fuel is being used, electrons and fusion products. The X-rays
radiate out in all directions while the ions and electrons are emitted along the anode axes, but in
opposite directions.

Most interestingly these units can be made in various sizes from a fraction of watt-hour, bench top unit and upwards. They all produce the same plasma characteristics (temperature and density) and radiation products providing uniform scalability. Only the size of the focus increases with unit capacity.

This sketch illustrates the basic principles of a plasma gun. Actual units look more sophisticated but adopt the same principals. Basically the inner and outer electrodes are separated by an insulator (dielectric material such as Pyrex). A fast acting switch (spark gap) creates a magnetic field surrounding the inner electrode (anode) and forms what is termed a plasma sheath on the insulator between 0.5 and 2 cm thick (Stage 1). As the current increases the sheath expands quickly in a radial path due to the magnetic field. There is an axial component of the magnetic field that pushes the plasma sheath axially towards the open end of the anode at around 10 kms/second pushing the fuel with it like a snow plough (stage 2). Here it encircling the anode where it starts to compress (Stage 3) and forms a hot dense plasmoid called a focus which is about a centimetre long and a few mm in diameter. Here the fuel becomes a plasma where it is trapped for a few nanoseconds with electrons discharging axially towards the left and ions to the right before the focus dissipates. Refinements to increase the density and extend the focus dwell time in order to generate fusion breakeven is LPP’s target.

Fig. 12.20: The basic components and action of a plasma gun. Courtesy: plasmafocus.net

Many fusion enthusiasts have waved aside the likes of plasma guns and other aneutronic fusion facilities as being impractical by suggesting they are being pursued by cranks working from their garage and that the generation of Bremsstrahlung will outstrip the fusion reactions. To their immense credit the proponents have doggedly persisted in their projects despite often being starved of much in the way of funding. In particular this can be said of Lawrenceville Plasma Physics (LPP) in New Jersey, USA who have consistently progressed with their plasma gun and Dense Plasma Focus developments. In 2012 they had fusion products using D-D reactions reaching temperatures of above 1.7 billion °K (150keV), densities of around 3 x 10^19/cm^3 and confinement times or dwell times of 7 to 30 nanoseconds.175 Way back in 2001 LPP also observed a triple product value of 5 x 10^15 keVsec/m^3 but the 2012 results indicate they have now left this record far behind. What is more, discovered by experiment and in the study of neutron stars, is that if the electron temperatures are considerably lower than that of the ions in the plasma (experienced when the magnetic fields inherent in the plasmoid are extremely high and in the 5 gigagauss range) the interaction between
ions and electrons reduce significantly allowing the fusion reactions to predominate over Bremsstrahlung production. LPP take the stance that they intend to exploit the instability characteristics of plasmas and use them to advantage.

As with other aneutronic units the plasma guns can be made very compact from bench top size to 5 MW and over capacity, with the possibility of direct electricity generation via one of several proven methods, thereby bypassing the expensive and inefficient turbine generator phase.

![LPP's concept of a 5MWe commercial DPF machine. LPP hopes to limit Bremsstrahlung to about 40% of total energy released and convert this back into electricity as the photons work their way through dozens of thin layers of metal giving off electrons. Hence, in this fashion some losses will be recovered.](image)

Fig. 12.21 LPP's concept of a commercial unit. Courtesy: LPP

**Tri Alpha:**

Yet another American organisation is working on aneutronic fusion but in a somewhat secluded fashion. Tri Alpha Energy (a name derived from p-B11 fusion products) is based in a business park near Irvine, California. It is rather secretive and their office is devoid of any company nameplates or logos.\(^{176}\)

It was established in 1998 and unlike some others in the field they have raised US$150 million privately from Paul Allen (Microsoft founder) and the Russian Government's venture capital firm, Rusnano.

Tri Alpha aim to develop a fusion reactor using p-B11 and/or D-He3 fuel. Burton Richter of Stanford University sits on the Board and the Advisory Committee recently told Deputy Science Editor of Science AAAS ‘I wouldn’t have spent 10 years on [Tri Alpha’s advisory] committee if it was working on a D-T system’.\(^{177}\) Just previously Tri Alpha were celebrating a confinement time for their C-2 fusion unit, claiming they had contained a plasma in steady state for 5 milliseconds at around 10 million \(^{6}\)K.

From the literature available it appears they too have adopted the FRC type CT with their magnetic bottle shaped plasma shaped like a cigar with hole through its axis. The \(\beta\) ratio (plasma pressure : magnetic pressure) is close to 100%, providing high density plasma.\(^{178}\)

As can be seen from Fig. 12.22 Tri Alpha’s model is a similar concept to that described for the Helion unit, where two opposing FRCs are fired into each other via plasma guns (reaching velocities of 160 kms/sec) into a single long lived (~ 1 ms) one. While it is decaying this single FRC shrinks into an even denser configuration. Meanwhile four neutral beam injectors fired tangentially and at an angle to the outer boundary (or separatrix) increasing its density and pressure.
Neutral beam injectors (yellow) heat and compact the combined FRC increasing temperature and density. Diverters at either end respectively collect the ions and electrons expelled along the hollow centre of the FRC. The 2ms should now read 5ms

Fig. 12.22 Tri Alpha’s unit Courtesy: Daily Mirror UK and The Last Tech Age

While only conceptional at this stage with both US and Russian finance, dogged determination by management plus 150 engineers engaged on the project we may be seeing something like this becoming reality in the not too distant future.

Fig. 12.23 Concept of a 2 x 50 MWe Tri Alpha power plant. Courtesy: Weller – Duke University

**Crossfire:**

CF Fusion Incorporated in Florida USA have developed a rather unique concept which they call their Multiphase neutral-plasma accelerator. They have a patent (Number WO 2014114986 A1) which is freely available. Their website www.crossfirefusion.com is very descriptive of their concept but as yet they have not published any results. They consider it could use multi fusion fuels
but the p-B11 would appear to be their main target.

In summary, while the information freely available on Crossfire indicates it to be a likely fusion game changer there is as of writing, no prototype reactor to support its operation in the real world. But in answer to our email Crossfire say they are hopeful this may eventuate in 2016.

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**Pros (aneutronic fusion)**

Could potentially allow aneutronic reactors to be located close to centres of demand and minimise electricity transmission losses - providing 24/7 energy. The bar may be extremely high and still yet may never be reached, but if it is then it is easy to imagine that one or more of these aneutronic designs will likely dominate the energy market.

99.8% p-B11 fusion products are the noble inert gas $^4_2\text{He}$ which will add to the earth's dwindling reserves.

The p-B11 fuel is plentiful. Reserves of Boric Oxide (B$_2$O$_3$) are estimated to be in the order of 210 million tonnes (i.e. 52 million tonnes of $^{11}_5\text{B}$). Separation of the two stable isotopes B10 and B11 is carried out by chemical means and both have uses in fusion power. Also hydrogen is extremely abundant on earth and the second most common element. Albeit hydrogen is currently most economical extracted from fossil fuels but it can easily be generated by electrolysis of waste or salt water by well proven chemical exchange processes.
Prospects of direct energy transfer between the fusion products to electricity by well-established methods. Simple compact designs and only 0.2% of energy from those damaging neutrons p-B11 fusion has to be one of the favourites in the fusion stakes setting nuclear fusion way in front of nuclear fission in view of fissions perceived image after Fukushima.

Space travel could be accelerated using aneutronic fusion engines and these projects have received much interest from NASA among others.

**Cons (aneutronic fusion)**

Although fairly minimal there will be neutron generation and associated radioactivity of the components.

D-He3 suffers from lack of He3 fuel reserves despite minimal amounts required per GWh. Furthermore the required triple product is not all that far above that of D-D which would possibly cause the latter reaction to predominate with associated neutron release.

Far less energy release per fusion pair for p-B11 than for D-T (8.7/17.6 = 0.49) and per kg (1.94/9.38 = 0.21) but still millions of times that of fossil fuels (e.g. diesel has approx. 0.000062% of equivalent inherent chemical energy by mass)

Target triple product values are 20 times higher than D-T for D-He\(^3\) and even higher for p-B11

Lack of government funding. While not actually a fault of the science, lack of government funding is definitely a great disadvantage when the potential for success could greatly reduce our carbon footprint. Projects like Missions to Mars, ITER and NIF appear to be more in vogue when it comes to government funding but should we ask whether these high profile projects will help to solve what seems to be one of the greatest problem this generation will ever face… (yes its global warming).

**12.11 Cold fusion in brief**

Much has been written about claims made by two chemists, Stanley Pons and Eric Fleischmann who in 1989 announced they had witnessed a fusion reaction of deuterium virtually at room temperature. Electrolytic cells fitted with a palladium electrode and filled with heavy water (D\(_2\)O) were said to have generated excess heat, neutrons and tritium. Palladium has a propensity to absorb considerable amounts of deuterium. Prominent journals published their findings only to retract them later. Sadly, after many trials worldwide none claiming to have been able to replicate their findings. Nonetheless several enthusiasts still pursue alternatives to the scientific trends such as bubble fusion claimed by Rusi Taleyarkhan of Perdue University in 2002 but with a similar outcome.

Brillouin Energy Corp promote their Controlled Electron Capture Reaction (CECR) which uses electromagnetic pulse to excite hydrogen 'at temperatures and pressures compatible with current industrial and chemical practices'. It is claimed the process converts the \(^1\)H first to \(^2\)H then through to \(^4\)H (which will have a half-life in nanoseconds to form \(^3\)_2He), then to \(^3\)_2He releasing 'a large amount of heat'. Several concepts for industrial use are offered to investors such as 5 to 10 MW boilers and a Hydrogen Hot Tube. A list of peer reviewed papers on low energy nuclear
reactions (LENR) is available on the site ftp://brillouinenergy.com. We will watch their progress with some interest.

Muon Catalysed Fusion (MCF) was studied in the early 1900s and is a well-established room temperature fusion phenomena. However net energy output is unlikely due to the energy required to produce sub atomic particles called muons. These have extremely short half-life (2.2 microseconds) making the pursuit of MCF of less interest in solving our energy problems.
13 Conclusion (Part 2)

There is an immense amount of work to do in a very limited time if we are to have a reasonable chance of staying within the tolerable global temperature increase of 2°C. Despite decades of warnings from very eminent climate scientists we, the human race, have been dumbing down or avoiding this major issue altogether, now to the extent that we are racing headlong dangerously close to what is meant to be our carbon safety barrier, as if it were a finishing line in a sprint race.

Political commitments at the UN Climate Conference in Paris (COP21) and before, while sometimes encouraging, will not, even if ratified, slay the carbon dragon.

Earliest fossils remain of our species Homo sapiens, suggest we began to develop around 195,000 years ago in Ethiopia and over thousands of years gaining larger, flatter skulls to hold a larger brain than all previous hominids. Fig. 4.1 temperatures show our species has actually witnessed a 2°C to 3°C increase and slightly higher around 120,000 years ago and some at least must have lived and bred. But what percentage is unknown and such is hardly a risk we should be imposing on our offspring, especially when we consider the many other environmental pressures we are placing on this earth in terms of deforestation, over-fishing and loss of topsoils.

We will have to universally agree to focus on the climate change issue. Stated targets like reducing emissions by 26 to 28% of 2005 levels by 2030, such as Australia has now espoused will not do the trick, particularly considering that 2005 was one of our highest pollution years. We have to be fossil carbon free by 2030 or at least very close to it.

In a perfect world, and with a hefty portion of guided democracy, we need to adopt something like sharing out the Carbon Budget among the various countries so that those less fortunate, and therefore less able to adapt to climate change, can be allotted the lions share. Hence, assisting the poorer countries to de-carbonise quickly and then allowing those countries to auction their remaining carbon credits globally. A sort of 'Cap and Trade' system but on a global basis.

One possible scenario is to:

- Divide the Carbon Budget of 850 Gt CO₂ stated in Chapter 1, or less on a purchasing power parity-gross domestic product-per capita (PPP GDP pa) basis. (PPP GDP is a means of equating purchasing power of goods and services in various countries by adoption of the term 'international dollar', with those living in others. An international dollar has the same purchasing power over GDP as the US dollar has in the USA). This data can be sourced by harmonising that which is provided by organisations such as World Bank and International Monitory Fund (IMF). This could be held in trust by an International UN body and not by the individual governments to discourage misappropriation or corruption.
- Provide long term loans via World Bank, International Monitory Fund, OECD or other groups. This could be monitored rigorously by the International UN body suggested above.
- Allow best practice companies to provide technical know-how to the poorer countries to enable them to replace whatever fossil fuel energy systems they possess, using the most of their natural resources to the LCA, EROI and LCOE ground rules.
- At the same time for so called developed countries in the OECD and beyond should press ahead with de-carbonisation under the LCA, EROI and LCOE ground rules regardless of their initial carbon credit issue and impose fairly punitive internal carbon and border carbon
taxes to discourage extravagant internal and imported fossil carbon generated goods and services. Any shortfall in carbon credits can later be purchased. Results will also be monitored internationally and final carbon credit balance should be positive. Debits on this score should attract international penalties.

- Carbon emissions to continue to be monitored world-wide. Source: Harmonised data from Carbon Dioxide Information Analysis Centre (CDIAC), Emission Database for Global Atmospheric Research (EDGAR) and BP etc.

- There will probably need to be a universal reserve maximum value placed on any carbon credits auctioned from the outset.

Needless to say such an endeavour would require the highest diplomatic and negotiation skills to be brought into being. Nonetheless such strident pathways as these are likely to be required if we are ever to succeed.

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So how would Australia fare under this scenario? Well according to the World Bank PPP-GDP pc figures in 2014 its initial carbon credit quota under such an arrangement would be worth around 0.49 Gt CO\textsubscript{2} and Australia's emissions of that year was 0.41 Gt CO\textsubscript{2} (although declining slightly over the last three years). So Australia would have to de-carbon very rapidly to avoid having to purchase more – hardly a likely outcome.

In comparison, China would be allotted just 1.6 Gt CO\textsubscript{2} and it's emissions that year was 10.4 Gt CO\textsubscript{2}, so it would definitely need to purchase more carbon credits.

Similarly the USA would gain just 0.39 CO\textsubscript{2} and it's emissions in 2014 was 5.3 Gt CO\textsubscript{2}

On the other end of the spectrum a country like the Congo would be allotted around 28.8 Gt CO\textsubscript{2} of carbon credits and it's emissions in 2014 were 0.01 Gt CO\textsubscript{2}, and Bangladesh would gain 6.9 Gt CO\textsubscript{2} of carbon credits and it's emissions in 2014 were 0.07 Gt CO\textsubscript{2}. So they would have a surplus of carbon credits giving an opportunity to raise living standards.

It is not hard to imagine rather vigorous resistance and lobbying from some of those living and operating in the more developed countries to this style of commitment, while the poorer and developing countries would most likely welcome it with open arms. It may be one reason we hear very little in the way of political proposals from politicians of any persuasion, along such lines.

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Then how should Australia address their part in the exercise? To show international goodwill perhaps the schedule should not exceed the 10 or so years in duration to achieve its de-carbonising target. Australia has a low population density and considerable, although variable, renewable energy resources in solar, wind, tidal and wave energy.

While there are several members of NGOs and academia who insists Australia can completely de-carbonise the grid with renewables alone. It would be most beneficial if this were proven to be the case in practice and there would also be all the other fossil fuels issues like transport to address. Rather than just mass adoption of this theoretical analysis and spending countless billions of dollars in the process only to find out several years down the track that it does not quite work without some additional alternative, should Australia first adopt a representative pilot scheme as suggested in Chapter 6? Our response is “Most definitely”.

While the current political scene in Germany with an average population density of around 227/km\textsuperscript{2} with only moderate solar insolation and wind resource argues they will succeed to de-carbonise just with renewables, and two of the less populated German states claim to have done just that re their
grid systems. Several British reviews on the other hand suggest Britain, with its slightly higher population density, will not be able to do this without support from nuclear plants. Britain would need offshore wind turbines located over an area 4 kms wide for the full length of its 3,000 km coastline to match the demand. Germany has just 80% of that figure in coastline and 25% greater population.

It would seem wise to continue research into biofuels and batteries and made available to all-electric and PVs plus reintroduce a Carbon Tax more on Norway's level including a border carbon tax.

Nuclear should not be ruled out until proven unnecessary. But for a country to maintain living standards anywhere near Australia's current one, reliable 24/7/365 electrical supply is most probably paramount.

CCS will most likely have an early demise due to the cost and lack of public support.

When questioned by Giles Parkinson of RenewEconomy on whether Australia can completely decarbonise the grid, Ergon Energy's CEO Ian McLeod responded:

“In short – it's technically possible for some grids with nuclear, geothermal and significant water resources, but it would be very difficult to do it economically for Australia due to our dry and flat continent.”

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Abbreviations & Conversion factors

AGR, advanced gas-cooled reactor
amu, atomic mass units
ANSTO, the Australian Nuclear Science and Technology
ARPANSA, Australian Radiation Protection and Nuclear Safety Agency
Bcft, billion cubic feet
BECCS, Bio-energy with Carbon Capture and Sequestration
BECS, Bio-energy with carbon storage
BEV, Battery electric vehicle
BP, British Petroleum
Btu, British thermal unit
BWR, boiling water reactor
CAT, computerised axial tomography
CCGT, combined-cycle gas turbines
CCS, carbon capture and storage
CDIAC, Carbon Dioxide Information Analysis Centre
CO, carbon monoxide
CO₂, carbon dioxide
CO₂eq, carbon dioxide equivalence (i.e. includes all greenhouse gases)
CO₂eq (IPCC 2014), carbon dioxide equivalence (i.e. includes all greenhouse gases, land clearing and degradation (albedo), dust, aerosols from volcanic action etc.)
COP, Conference of Parties
CPV, Concentrated photovoltaic
CSP, concentrated solar power
CT, compact toroid
DAR, Direct Air Capture
DCF, discounted cash flow
ECS, Equilibrium Climate Sensitivity
EDGAR, emissions database for global atmospheric research
EIA, US Energy Information Administration
EOR, Enhance Oil Recovery
EROI, energy return on investment
FTS, Fischer- Tropsch Synthesis
eV, electron volt
GDP, gross domestic production
m, metre
MAGNOX, MAGnesium OXide fuel clad reactor
Mboe, million barrels of oil equivalent
MeV, mega electron volt
MHD, magneto hydrodynamic
MIT, Massachusetts Institute of Technology
MOX, Mixed oxide nuclear fuel
MPa, megapascal
MW, megawatt (primary energy)
MWe, megawatt (electrical energy)
MWh, megawatt hour
NCR, National Research Council
NEA, nuclear energy agency (USA)
NIF, National Ignition Facility
NPT, Nuclear Non-proliferation Treaty
NOx, nitrogen oxides
NRC, National Research Council
NRL, Naval Research Laboratory
NREL, National Renewable Energy Laboratory
OECD, Organisation of Economic Cooperation and Development
PFR, prototype fast reactor
PHEV, Plug in electric vehicle
PHWR, pressurised heavy water reactor
PJ, peta Joules
PCC, post combustion capture
PUREX, plutonium, uranium extraction
ppbv, parts per billion by volume
ppmm, parts per million by mass
ppmv, parts per million by volume
PPP, purchasing power parity
PV, photovoltaic
PWR, pressurised water reactor
RBMK, Reaktor Bolshoy Moshchnosti Kanalnyy (as per Chernobyl)
SCWR, supercritical light water reactor
SGHWR, steam generating heavy water reactor
SPK, synthetic paraffinic kerosene
SUV, sports utility vehicle
SWU, separative work unit
TWh, terawatt hour
UEA, University of East Anglia
UNFEO, United Nations Food and Agriculture Organisation
UNSCEAR, United Nations Scientific Committee on the Effects of Atomic Radiation
UNFCCC, United Nations Framework Convention on Climate Change
WHO, World Health Organisation

Energy 1 kWh = 3.6 million Joules (MJ) = 3413 BTU s = 0.086 kg oil equiv. (kgoe)
= 2.247 x 10^25 electron-volt

Power 1 MW = 1,341 horse power (HP)

Pressure 1MPa = 10bar = 145psi = 102m Water Gauge

1 Barn = one trillion trillionth of a cm^2

1A$ at time of publishing = US$0.788, €0.6968, £0.5547, NOK6.5028, ¥87.12
Appendix 1 – Climate change in detail

Greenhouse gases act in the atmosphere like one or more blankets on our beds. If we didn’t have this blanket of non-condensable greenhouse gases earth would become an icebound planet\(^{181}\). If we are at an uncomfortable temperature bed wise we can add or remove blankets. But we have only been adding blankets almost unwittingly to our atmosphere since 1750 and the start of the Industrial Revolution.

The term greenhouse gas is meant to refer to a number of gases that have the ability to reflect infra-red heat. As when sunlight passes through a greenhouse window some of it changes wavelength to infra-red range (heat) which is less transparent in regard to the glass. Hence the greenhouse warms up. The atmosphere acts somewhat differently but a greenhouse is a good analogy. The gases in question include, but not limited to the following:

<table>
<thead>
<tr>
<th>Greenhouse gas</th>
<th>Chemical notation</th>
<th>Source</th>
<th>Mean lifetime in atmosphere (years)</th>
<th>Global Warming Potential (100 year horizon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>CO(_2)</td>
<td>Fossil fuel combustion, cement/lime kilns, iron smelting, forestry clearing</td>
<td>~100 or more years</td>
<td>1</td>
</tr>
<tr>
<td>Methane (Natural gas)</td>
<td>CH(_4)</td>
<td>Mining, swamps, rice paddies, landfill sites</td>
<td>12 years</td>
<td>25</td>
</tr>
<tr>
<td>Nitrous Oxide</td>
<td>N(_2)O</td>
<td>Fertilisers, combustion</td>
<td>114 years</td>
<td>298</td>
</tr>
<tr>
<td>Ozone</td>
<td>O(_3)</td>
<td>Combustion, solvents, electrical arching</td>
<td>hours-days</td>
<td>N/A</td>
</tr>
<tr>
<td>CFC-12</td>
<td>CCl(_2)F(_2)</td>
<td>Dry cleaning fluids, fire extinguish foams</td>
<td>100 years</td>
<td>10900</td>
</tr>
<tr>
<td>HCFC-22</td>
<td>CHClF(_2)</td>
<td>Refrigerant replacing the CFC-12</td>
<td>12 years</td>
<td>1810</td>
</tr>
<tr>
<td>Sulphur Hexafluoride</td>
<td>SF(_6)</td>
<td>HV switchgear (dielectric substance)</td>
<td>3200 years</td>
<td>22800</td>
</tr>
<tr>
<td>Water vapour</td>
<td>H(_2)O</td>
<td>Combustion, evaporation, melting ice</td>
<td>9 days</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table A1.1 Greenhouse gases - The major players

While the impact of some greenhouse gases is far more potent than that of CO\(_2\) because of its concentration, CO\(_2\) takes
front stage and is the elephant in the room so to speak. While water vapour has far more influence (as an amplifier of other gases when present) than CO$_2$ it is not an absorber re-emitter itself. Nonetheless it may well turn out to be the joker in the pack because of this influence. University of NSW Professor Steven Sherwood’s report indicates that the Earth cooling property of water vapour (once it forms clouds) may be over stated in much of the climate models thereby producing optimistic results regarding likely temperature change by 2100. Instead of clouds taking on a role of reflecting sunlight back out to space when water vapour is drawn is down to lower levels switches its role to amplifying the warming impact of CO$_2$ etc.

Methane molecules have far more clout (about 25 times on a hundred year time-scale but 72 times on a 20 year time-scale) than one of CO$_2$ but for the present at least is far less abundant in the atmosphere and stays there much less before itself breaks down to CO$_2$ and water vapour after a while hence the decline in its impact. Over time

What makes some gases act as they were like glass in a greenhouse relates to their molecular structure and vibration? Visible light from the sun is absorbed by the land and ocean surfaces and is transformed into heat which re-radiates in the form of invisible infra-red radiation. In an atmosphere devoid of greenhouse gases the heat would radiate back into space more or less in equilibrium but at night all the remaining heat would radiate back up into space such that the night time side of the earth's temperatures would drop dramatically, to well below zero. With the presence of greenhouse gases their molecules actually absorb the heat and re-radiate it in all directions thus reducing the amount of heat radiated out to space. These special molecules are responsible for the current conditions in the biosphere that have allowed our species and most others to have evolved and have determined our 'design'. We are not equipped to step too far out of our comfort zone to the extent and within the time frame our climate is now changing.

The main constituents of our atmosphere are Nitrogen (N$_2$ at 78.08%) and Oxygen (O$_2$ at 20.95%). There molecules each consist of two atoms of the same element which are too closely bound to vibrate and hence do not change the frequency of the visible light to any appreciable amount. Conversely to this the greenhouse gases have other component atoms, are loosely bound and resonate by vibrating when struck by a light photon. The resulting frequency change of the sunlight morphs more into the infra-red frequency or more heat.
Fig. A1.1 The main players – Oxygen does absorb some infra-red but then forms Ozone which acts to protect us from harmful Ultra Violet radiation.

Sunlight is an electro-magnetic radiation. It has a wavelength varying from 0.2 to 4 microns i.e. a micron (µm) is one millionth of a metre and can be regarded as a wave as well as being made up of particles (photons). The visible part of the electro-magnetic spectrum ranges from violet (0.38 µm) to red (0.76 µm). Some of the solar radiation from the sun on striking the atmosphere is reflected by what are termed high albedo (reflective) surfaces like ice, snow and high level (over 9 km above earth) clouds. That which enters the atmosphere is somewhat eroded by absorbing molecules of the gases shown in Fig. A1.2.

![Solar spectrum](image)

Fig. A1.2 Impact of gases on the incoming solar spectrum.

Oxygen (O₂) in the atmosphere is broken up by the ultraviolet radiation (UV) into 2 single oxygen atoms. These then recombine and sometimes into groups of 3 atoms forming an ozone molecule (O₃) which in turn traps considerable amounts on UV at high stratosphere altitudes protecting us from much of the skin damage it would otherwise inflict. At the lower troposphere altitudes it can act as a greenhouse gas. The various greenhouse gases absorb various wavelengths of infra-red radiation as shown re-emitting same in all directions. Downward directed scatter is what creates our protective blanket. As we increase these gases in the atmosphere however the 'blankets' are piling up to a dangerous degree.

What actually finally gets re-radiated from the earth back into space as infra-red spectrum is slightly less than the incident radiation and much of the balance incurs a marked shift to the longer wavelengths of infra-red radiation. Fig. A1.3 is an extended representation of the above Fig A1.2 and the reflected spectrum.
By way of explanation, firstly the top section (Spectral Intensity) the red curve line is the spectrum of wavelengths for the sun at a surface temperature of 5525 K (Kelvin – Absolute zero temperature, i.e. the coldest we could ever achieve and equivalent to minus 273.15 C degrees). The violet blue and black lines represent that of the earth’s spectra of 310, 260 and 210 K respectively and the large portion of infra red radiation that does escape being ambushed by the greenhouse gases is shown in blue with a wavelength of around 10 microns (10 µm) directly under the blue curve’s peak.

The grey portions of the next lower section (Percent) represents the blocked wavelength form the combined action of the greenhouse gases which are individually depicted in grey in the lower (Major Components) sections. Rayleigh scattering shown in the bottom section is a feature of the UV/violet end of the solar spectrum which gets modified on entry scattering the violet and blue photons. The human eye is less sensitive to violet and hence we see the cloudless sky as blue.

The rather complex Figs A1.4 & 5 indicate that while the solar radiation energy incoming (typically shown as 342 Watts/m^2) is balanced by that re-radiated by the upper atmosphere (stratosphere) the lower atmosphere cannot get rid of its excess heat to the tune of 0.6 or so Watts/m^2 due to the greenhouse gasses.
The 5.4% purple squiggle represents normal conduction and convection of heat from the earth's surface in the form of thermals. These create the weather. The 25.4% purple dotted arrow represents a change in state of water by evaporation and transpiration. This feeds the weather. The orange arrows represent the infra red radiation paths of which only a portion is reflected back into space.

The solar energy input is shown as 100%. The output to space (22.6 + 6.7 + 70.5 = 99.8% indicating the net absorbed by the atmosphere is 0.2% resulting in the greenhouse effect.

The average global temperature is determined by the amalgamation of information from thousands of meteorological stations, satellite information and ocean surface and underwater measurements taken around the globe on a regular basis.

So what all this about; a 2°C warmer threshold we are told we must avoid? The frequently quoted reference to limiting global average temperature increases to 2°C seems ubiquitous, but literature varies considerably on what the deciding parameter actually is. Some say it will be caused by a doubling of pre industrial age (mid 18th Century) i.e. from 287 parts per million by volume (ppmv) to 574 ppmv. Others say 400, 450, 560 ppmv and so on, plus confusion on the year by which we need to reach the limit by.

The origin of the 2°C notion seems rather vague being attributed to an economist in 1975 by a William D Nordhaus in his paper relating to the trade-off between growth and environmental quality.

Since then it appears to been taken up by some scientists, politicians, policy makers at Kyoto and
later Climate Change conferences and in 2005 the International Panel on Climate Change stated; 'For example, limiting warming to 2°C above pre-industrial levels with a relatively high certainty requires the equivalent concentration of CO₂ to stay below 400 ppm'.

On the surface it seems a simple measurable parameter that most people can grasp but has of late generated much controversy. Firstly there is some confusion as to the meaning. If we regard say 1.5°C average increase in global temperature as being reached so 'turn off the greenhouse taps' this will not necessarily lead to a final 2°C rise due to inertia in the global system. A bit like lifting your pedal off the car's accelerator without applying the brakes the vehicle will continue to move and even speed up if on a downward slope (i.e. a positive feedback due to gravity). The oceans store much heat and CO₂ but this will ultimately be released to the atmosphere after a time as the oceans warm up. Further the warmer the atmosphere the greater amount of water vapour it can hold and water vapour, as mentioned, is itself a greenhouse gas which can amplify the impact of other such gases to the order of 2 or 3 times their 'marked up' value by its positive feedback function. So that final average global temperature could well finally exceed the nominal 1.5°C and go way beyond the 2°C threshold.

Just how the atmosphere will react to an increase in a certain input of greenhouse gases has been difficult to predict but the IPCC and other bodies have rationalised the effect of doubling the greenhouse gas concentrations over pre industrial times (i.e. to 2 x 280 or 560 ppmv CO₂) or what is referred to as the Equilibrium Climate Sensitivity (ECS) lies somewhere between 1.5 and 4.5°C and there is growing evidence that 3°C is close to the true value. Hence earlier climate models using the lower end of the ECS spectrum have tended to be optimistic as to how we were travelling climate wise and giving the impression we have more time to fix the issue than actual.

Many scientists also indicate that 2°C increase is far too high. NASA's James Hansen after studying Palaeolithic records going back 50 million years says just 450 ppmv will melt a significant portion of the earth's ice and permafrost thereby releasing large amounts of methane clathrate (basically natural gas in semi liquid form) and thus greatly adding leverage to the overall damaging impact.

Others state we should adopt a 1°C increase as anything over will have the same negative impact that was earlier thought of 2°C. Others argue it should be 1.5°C. A conference held in the University of Melbourne July 2011 advised 'The international community has agreed to limit global warming to 2 degrees Celsius above pre-industrial levels. Yet the Copenhagen pledges to cut emissions will, if honoured collectively, result in average warming of 4 degrees or more.'

Others argue we should drop the 2°C as a milestone altogether as it does not fully represent the affects of inertia, especially that of the oceans. An article appearing in Nature 1st October 2014 suggests we should adopt instead a more comprehensive suite of indicators including ocean temperatures and acidity as being far more appropriate.

An organisation found at 350.org was established in 2008 calling for a 350 ppmv limit when the global CO₂ level was already just under 386 ppmv. The 350 organisation supports scientific claims by NASA’s James Hansen et al that 350 ppmv is the maximum safe level of greenhouse gases in the atmosphere to avoid dangerous tipping points (the point at which a series of small changes or incidents becomes significant enough to cause a larger, more important change e.g. melting of the vast areas of permafrost thereby releasing massive surges of methane). Such events would result in humanly irreversible climate disasters.
We have already reached 400 ppmv CO$_2$ and an estimated 435 ppmv CO$_2$eq (IPCC 2014) level. The National Oceanic and Atmospheric data Centre (NOAA) advise the increase in average combined (land and ocean) global temperature is over 0.68°C degrees above the 20$^{th}$ century average of 14°C, the warmest such period (Jan to November) on record. They further advise that the global surface temperature (land only) was 0.82°C and the ocean surface by 6.9°C above the 20$^{th}$ century average. Oceans take longer than land masses to warm up and cool off so it’s a case of watch this space.

What is concerning is that there does not appear to be any real consensus to replace the 2°C mantra any time soon. The IPCC which has been commissioned to study the problem since 1988 now states:

IPCC’s latest (2014) Mitigation of Climate Change report following many scenarios on Climate Change mitigation however states:

'Mitigation scenarios in which it is likely that the temperature change caused by anthropogenic GHG emissions can be kept to 2°C relative to pre-industrial levels are characterised by atmospheric concentrations in 2100 of about 450 ppm CO$_2$eq (high confidence). Mitigation scenarios reaching concentration levels of about 500 ppm CO$_2$eq by 2100 are more likely than not to limit change to less than 2°C relative to pre-industrial levels.'

It seems our game plan should be to target the 450 ppmv (read ppmv) CO$_2$eq level by 2100 or at least 500 ppmv and without overshooting and having to attempt to draw back CO$_2$ from the atmosphere in the latter half of the century. The CO$_2$eq classification means the impact of all long term greenhouse gases in accordance with what is known as their Global Warming Potential (GWP see Table A1.1). The greenhouse gases therein included are CO$_2$, methane (NH$_4$), Nitrous Oxide (N$_2$O) and so called halocarbons (CFCs and similar) plus minor players. This figure in 2013 was already 478ppmv$^{187}$. The relationship between the straightforward CO$_2$ ppmv reading (blue line) and the CO$_2$eq (black line) can be seen in Fig A1.5.
The actual CO$_2$ and other greenhouse gas atmospheric readings are constantly being monitored by several organisations including CSIRO at Cape Grim Tasmania [http://www.csiro.au/greenhouse-gases/]. The CO$_2$eq is calculated by multiplying all the long lived GHG readings (ppmv or ppbv) by their respective Global Warming Potential (GWP) and adding up. It is this figure that determines how the so called radiative forcing factor (W/m$^2$) will eventually rise to. This factor (identical to that of solar radiation) in turn determines what the eventual temperature rise (or possibly drop) will be. The AGGI line represents the change in this value since 1990.

In the case of IPCC statement above the 450 and 500 ppmv which we have previously labelled CO$_2$eq (IPCC 2014) also included the components with negative GWP such as volcanic aerosols, high level clouds and reflective surface characteristics like snow. These additions appear to reduce the 2011 NOAA figure (http://www.esrl.noaa.gov/gmd/aggi/aggi.html) of 471 CO$_2$eq ppmv somewhat down to 430 CO$_2$eq (IPCC 2014) ppmv stated for 2011 i.e. the IPCC's definition figure is about 9% below the NOAA figure and 11% above the CO$_2$ alone atmospheric levels of that year$^{188}$. But the IPCC’s own previous document states$^{189}$ that negative values they used are with a low to medium level of confidence and range their 430 CO$_2$eq (IPCC 2014) ppmv between 340 and 520 ppmv. So there is some degree of risk even with the 450 ppmv CO$_2$eq (IPCC 2014) target. NOAA’s 2014 figure is 481 CO$_2$eq ppmv.

Fig. A1.5 As per fig A1.4 but with Watts/m$^2$

Again the shortfall in the heat reflected back into space is 340.4-77.9-22.9-239.9 = 0.6 Watts/m$^2$. This is what is causing the earth to warm up.
Methane:
Second only to CO$_2$ in regard to greenhouse gas impact is methane (NH$_4$). Atmospheric methane concentration has tripled since 1750 and is growing at around 0.3% pa. While the current concentrations in our atmosphere seem quite low at around 1820 parts per billion by volume (ppbv) as mentioned its impact in the atmosphere per molecule is some 25 times greater than CO$_2$ based on a 100 year time frame. Over a shorter period it has even much more ‘grunt’ as over time it tends to break down to CO$_2$ and water vapour by a reaction with the hydroxyl radical -HO (neutral version of the hydroxyl ion -HO) present in the atmosphere. For example the GWP of methane over 20 years is 72. As a result it currently appears to represent 17% of the radiative forcing (warming potential on 100 years time frame) as opposed to CO$_2$ which drives 65% but methane may therefore maybe likely to have far more impact over the crucial next two decades.

There appears to be some difference between what the World Bank considered as the 2010 global emissions of methane (7,515 million tonnes CO$_2$eq) and those of the US EPA (7195.6 million CO$_2$eq). The US EPA data does contain information from considerably more sovereign states than the former so for this document we are quoting their figures.

US EPA further advise that world methane emissions are anticipated to reach 7,888 million tonnes CO$_2$eq by 2020 and 8,586 by 2030. Methane release from natural gas and oil systems alone are expected to amount to 1,912 million tonnes CO$_2$e in 2020 and 2,113 in 2030. Australia’s contribution in 2010 was 116 million tonnes CO$_2$eq anticipated to grow to 126.6 million tonnes CO$_2$eq in 2020 and 138.4 in 2030.

There is a positive effort in the USA to reduce the amount of methane released, especially in the petrochemical industry. US EPA refer to their Natural Gas Star project which advises oil and natural gas companies on how they may be able to reduce their methane emissions due to the gas' escape during all sections of their operations. In 2010 they were successful in reducing emissions by 1.9 billion tonnes (96Bcf) which is impressive. But the 2013 the emission figures released by them (7.6 billion tonnes (377Bcf) show there is still some way to go$^{190}$. Over 39% of this occurs during production (well extraction).

Fig A1.6 Atmospheric Methane trends. Courtesy; NOAA

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The thing is, what do you do with the methane once captured? Well it turns out to be far less impact on global warming if it is simply used as a fuel. The 100 year GWP of methane as stated is 25. If completely burnt to CO₂ and H₂O one unit of methane produces approx 2.73 units of CO₂. Thus the result of burning, rather than emitting methane is to reduce its CO₂eq impact by a factor of 25-2.73 = 22.27. So, assuming it has all been burnt, the 2010 reduction would have reduced the CO₂eq figure by over 42 million tonnes.

The above world figures do not include natural methane emissions which would add another 29%. But that process has been going on for millennia and does not play a part in the post Industrial Age atmospheric increases. The break up is given in Fig. A1.7.

![Methane Sources](image.png)

**Fig. A1.7 Sources of methane. Courtesy: GISS/NOAA**

Natural sources are mainly from microbial action on vegetation in wetland and oceans. Termites use their internal microbes to break down cellulose. Rice growing is an example of the anthropogenic wetland discharge sources. Enteric fermentation refers to emissions from livestock like cattle and sheep.

Of major concern is the impact of the growth of all greenhouse gases and global warming will trigger release of methane that has been trapped in permafrost and the Arctic Ocean floor for millennia. There is evidence that this may already have started.

**Nitrous Oxide:**

Nitrous Oxide levels in the atmosphere along with the halogenoalkane CFC-12 represent the third biggest contributors to so called radiative forcing or Climate Change, each representing 6%. Nitrous Oxide has GWP of 298 at both 20 and 100 year time scales compared with 1 for CO₂.
Halogenoalkanes:

Thankfully the impact of some of the halogenoalkanes, the once hailed super synthetic gases, is declining in the atmosphere. Some are not only greenhouse gases with high GWP but are the main contributors to the ozone depletion in our stratosphere. The CFCs were developed starting in the 1930s as refrigerants, propellants for aerosols, generating foamed plastics like expanded polystyrene and dry cleaning compounds. They were not very toxic and were non-flammable. Unfortunately for these incredibly useful artificial chemicals, in 1974 two scientists M Molina and F Rowland argued that if these ever reached the stratosphere they would breakdown to release chlorine free radicals that would then react with ozone molecules to reduce them to normal oxygen molecules (O₃ to O₂) removing much of our protection from ultra violet radiation from the sun. Following reports from studies in Antarctica 1986 their theory was transformed into fact in the form of the hole in the ozone layer and global efforts were made to phase them out by replacing with less damaging synthetic compounds such as HCFC-22 and HFC-134a. Molina and Rowland, along with their colleague Paul Crutzen were both awarded Nobel Prizes in 1995.
Fortunately the concentration in the atmosphere of the old refrigerants like CFCs is declining while those of the new less harmful replacements increase due to accidental or negligent release.

HCFC-22 has only one twentieth the impact of CFC on the ozone layer and HFC-134a has none. Nonetheless all have massive GWP as Fig A1.9 and Table A1.2 imply.

<table>
<thead>
<tr>
<th>Halogenoalkane</th>
<th>Formula</th>
<th>GWP @ 20 years</th>
<th>GWP @ 100 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC-11</td>
<td>CCl₃F</td>
<td>6,730</td>
<td>4,750</td>
</tr>
<tr>
<td>CFC-12</td>
<td>CCl₂F₂</td>
<td>11,000</td>
<td>10,900</td>
</tr>
<tr>
<td>HCFC-22</td>
<td>CHClF₂</td>
<td>5,160</td>
<td>1,810</td>
</tr>
<tr>
<td>HFC-134a</td>
<td>CH₂F-CF₃</td>
<td>3,830</td>
<td>4,470</td>
</tr>
</tbody>
</table>

Table A1.2 Greenhouse Warming Potential of Halogenoalkanes

It should be widely known that there is often more CFCs trapped in the polystyrene insulation of old refrigerators and air conditioners than in their compression systems so simply recovering draining and destroying the CFCs in the latter is less than half the clean-up job.

**Sulphur Hexafluoride SF₆:**

The most potentially dangerous GHG is sulphur hexafluoride SF₆ with a GWP of 16,300 over 20 years and 22,800 over 100 years and with a lifespan of 3,200 years. It is used as an electrical insulator in switchgear due to its excellent dielectric properties. It is another colourless, odourless gas. Despite its potency there are demonstration clips on YouTube of folks inhaling same to lower the pitch of their voices. One is or was here [https://www.youtube.com/watch?v=winZR7JqxBs](https://www.youtube.com/watch?v=winZR7JqxBs)
Fig A1.10 SF6 atmospheric concentration in parts per trillion by volume as a result of releases or accidents in the electrical industry. Courtesy: Environment Canada

There are many other GHG but the main ones have been covered here.

One all important IPCC 2014 table is shown below Table A1.3

<table>
<thead>
<tr>
<th>CO₂eq Concentrations in 2050 [ppm CO₂eq]</th>
<th>Subcategories</th>
<th>2011–2050</th>
<th>2015–2040</th>
<th>2050</th>
<th>2100</th>
<th>Temperature change (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total range ≤ 450</td>
<td>1.5°C</td>
<td>2.0°C</td>
<td>3.0°C</td>
<td>4.0°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>450 (420–480)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Unlikely</td>
</tr>
<tr>
<td>500 (480–520)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Unlikely</td>
</tr>
<tr>
<td>550 (530–580)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>More unlikely than likely</td>
</tr>
<tr>
<td>600 (580–650)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Likely</td>
</tr>
<tr>
<td>650–700</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Likely</td>
</tr>
<tr>
<td>&gt;700</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>More unlikely than likely</td>
</tr>
</tbody>
</table>

Table A1.3 As shown we need to keep the CO₂eq (IPCC 2014) count to 450 ppmv or lower to have any real chance of limiting the increase in Global average temperatures to 2°C. Note the “relative to 1850–1900” temperatures which were approximately 0.8°C. Lower than today. Anything higher than 500 ppmv with no overshoot before 2100 would involve having to extract massive quantities of emissions from the atmosphere and sequestering same somehow and/or re-afforestation on a large scale. IPCC are suggesting growing and harvesting biomass, combusting, capturing the GHG and sequestering same underground. This will present several negative issues (see Appendix 5)
CO₂ eq ppmv figures which include the main greenhouse gases in the atmosphere are regularly recorded by CSIRO, NASA, NOAA and others, and there is close agreement between them. Unfortunately there are none which also include the potentially cooling aspects of aerosols and such which form a part of the CO₂ eq (IPCC 2014) criteria.

On the other hand there are regular compilations of greenhouse gas emissions from countries, mainly CO₂, by organisations such as the World Bank, USEIA, Enerdata, Global Carbon and EDGAR which basically rely on reports of emissions from the various world government bodies. These are not as consistent as you can imagine and can differ as much as 5Gt CO₂ from one another in any one year. Also their average year by year CO₂ growth rates can vary between 2.2% and 3.2% pa. Notwithstanding the variations it is pretty clear of where we were at in 2011 and where we need to head for in order to give us some reasonable chance of holding the average global temperature rise to 2°C. Clearly if we keep going as we have been (business as usual) we will simply ‘cook’ the planet.

Fig. A1.11: Some contributors to atmospheric GHGs
Appendix 2 – Energy in more detail

The scientific/engineering definition of energy is the ability to do work. Objects can have energy by virtue of their motion (kinetic energy), by virtue of their position (potential energy), chemical energy by virtue of the chemical's ability to combine with others or transform to others, or by virtue of their mass (i.e. $E=mc^2$).

A typical example of **kinetic energy** is any given body that is in motion, e.g. moving vehicle, flowing water, speeding bullet. The energy relationship is given by $E_k = \frac{1}{2} mv^2$ where $m$ is the mass of the body and $v$ is its velocity. Hence a person of say 90 kg mass running at 8 metres/second would possess a kinetic energy of $E_k = 0.5 \times 90 \times 8 \times 8 = 2880$ Joules = 0.0008 kWh

An example of **potential energy** is any given body that is at a height above a reference elevation (gravitational) e.g. Olympic dive contestant, a bolder on a ledge, water in a dam. It could also relate to the elastic energy in a coiled spring, the chemical energy of some substance, the magnetic energy due to a body's magnetic charge or electrical in relation to a body's voltage. The gravitational energy relationship is $E_p = mgh$ where $m$ is again the body's mass, $h$ is its height above some reference and $g$ is the earth's gravitational constant 9.8 m/s$^2$. Hence the same 90 kg person ready to dive off a 10 metre diving board would have potential energy of $E_p = 90 \times 9.8 \times 10 = 8820$ Joules = 0.00245 kWh

With reference to issues involving emission of greenhouse gases refers to **chemical energy** i.e. the fuel's potential energy in relationship to what its thermal (chemical) energy would be after complete combustion. This applies to both fossil fuels (coal, oil, coal mine gas) and cyclic fuels (wood, bagasse, palm oil etc.) But in the case of the latter the resulting CO$_2$ is in a constant evolutionary cycle in the biosphere whereas the fossil fuels have been locked up in the earth's crust for millennia until we started to extract them. Hence the resulting fossil emissions are building up in the atmosphere

There is also a whole spectrum of electromagnetic wave energy such as light, infra red heat, radio waves. Quantum mechanics demonstrates that these waves can also be considered as particles e.g. a light photon which if so directed can ‘knock out’ an electron in an atom of the dielectric component of a photovoltaic (PV solar) cell which will contribute to the flow of electricity to your home or to the grid.

The thermal energy combustibles posses are referred to as their heat or calorific value. The total heat value is referred to as the Higher Calorific (or Heat) Value (HCV or HHV). As many combustibles contain hydrogen which is combustible to water vapour only the so called sensible
heat (heat that relates to a change in temperature) is usually recovered or partly so. The latent heat (heat relating to a change in phase e.g. water vapour to water liquid) is not associated with a temperature change and is usually not recovered in practise. The Lower Calorific (or heat) Value (LCV or LHV) represents the sensible heat content. Table A2.1 is repeated here again for convenience.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>LCV MJ/kg</th>
<th>LCV kWh/kg</th>
<th>CO₂ kg release/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>121</td>
<td>33.6</td>
<td>0</td>
</tr>
<tr>
<td>Anthracite</td>
<td>36</td>
<td>10.0</td>
<td>0.35</td>
</tr>
<tr>
<td>Thermal (power station) coal</td>
<td>25.5</td>
<td>7.1</td>
<td>0.32</td>
</tr>
<tr>
<td>Brown coal (liquefied)</td>
<td>10</td>
<td>2.8</td>
<td>0.31 to 0.33</td>
</tr>
<tr>
<td>Coke</td>
<td>20 to 22</td>
<td>5.7 to 8.3</td>
<td></td>
</tr>
<tr>
<td>Natural gas (Australia)</td>
<td>55</td>
<td>15.3</td>
<td>0.18</td>
</tr>
<tr>
<td>LPG</td>
<td>45.7 to 46.3</td>
<td>12.7 to 12.9</td>
<td>0.23</td>
</tr>
<tr>
<td>Biomass</td>
<td>12 to 20</td>
<td>3.3 to 5.6</td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td>15 to 19</td>
<td>4.2 to 5.3</td>
<td>0.07**</td>
</tr>
</tbody>
</table>

Table A2.1 some LCV values of combustibles

Now the eminent physicist and Nobel laureate Albert Einstein in 1905 introduced us to several amazing facts in his paper 'Special Theory of Relativity' of which his incredibly simple formula relating energy to mass \( E=mc^2 \) was implanted. The \( m \) refers to the mass of an object in kilograms (kg) and \( c \) is the speed of light in metres per second (m/s) to give the energy embodied in the object \( E \) in joules (J). As the speed of light is close to 300 million m/s and as this value in the formula is squared it can be seen that amount of energy as a result of a difference in mass is astronomical. While the equation applies to any object capable of changing state, including the mass of any combustible, it is only really physically detectable in nuclear reactions where the mass of the resultant parts varies from the original group of atoms because the relative energy of nuclear reactions is very much greater than those of combustion. Table A2.2 illustrates the relative energy release.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TJ/kg fuel</td>
<td>1.42E-004</td>
<td>3.66E-005</td>
<td>3.28E-005</td>
<td>83.14</td>
<td>83.61</td>
<td>104.64</td>
<td>68.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>kWh/kg fuel</td>
<td>39.36</td>
<td>10.16</td>
<td>2.31E+007</td>
<td>2.32E+007</td>
<td>2.89E+008</td>
<td>1.54E+007</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Products</td>
<td>H₂O</td>
<td>D₂O</td>
<td>CO₂</td>
<td>Spectrum</td>
<td>Spectrum</td>
<td>iH + n</td>
<td>iH + T</td>
<td>H &amp; ²H⁺ + n²</td>
<td>3 x iH⁺</td>
</tr>
<tr>
<td>% of (H + H) fusion</td>
<td>0.000042%</td>
<td>0.000011%</td>
<td>0.000010%</td>
<td>24.48%</td>
<td>24.62%</td>
<td>100.00%</td>
<td>306.82%</td>
<td>20.57%</td>
<td></td>
</tr>
</tbody>
</table>

Table A2.2 showing energy comparisons between combustion and nuclear reactions.

The heat derived from combustible fuels comes mainly from the burning of their two main components, hydrogen and carbon. While the energy derived from burning a kilogram of hydrogen is more than 4 times that of the same mass as carbon it itself pales into insignificance when compared to the heat generated in nuclear fission reactions. These in turn generate about a third of the heat generated by the most likely first commercial fusion reaction, namely Deuterium and Tritium nuclei fusion. Deuterium and Tritium are both isotopes of hydrogen. See Chapters 9 & 10 for more nuclear information.

An example of mass loss to energy is when a single atom of the fissile isotope of uranium \(^{235}\)U
absorbs a neutron. There is a whole range of possible resultant isotopes with varying degrees of occurring. One common set of results is radioactive isotopes Krypton and Barium plus 3 released neutrons. (The gain in neutrons is what facilitates the chain reaction in fission. Fig A2.1 illustrates the process.

![Fig A2.1 One possible fission scenario](image)

Adding up and comparing the total mass of fuel and fission products indicates the loss of mass. The fuel side adds to 263.052595 atomic mass units (amu) which equates to $3.91975 \times 10^{-25}$ kg. The fission product side adds up to 235.86656221 amu or $3.91666 \times 10^{-25}$ kg. So there is a minute loss of $3.08915 \times 10^{-28}$ kg so the energy release ($\Delta mc^2$) works out at $2.776389 \times 10^{-11}$ Joules. But there are an immense number of fissions acting at any one time and the complete fission of just one kg of $^{235}$U yields $1.97 \times 10^7$ kWh. If we compare this with the equivalent energy release by burning thermal coal at $7.25 \text{ kWh/kg}$ (Chapter 2 Fig 2.1) we would need over 2,700 tonnes of the fossil fuel.

The second law of thermodynamics when related to heat engines basically says that we can never get 100% heat conversion to useful work. The key word is 'useful'. The first law of thermodynamics states all energy is conserved but in motor vehicles, planes, lawn mowers and power stations alike we can never convert all the thermal energy of the fuel to motion. There will be losses. For a typical power station their will by boiler/reactor losses, steam cycle (Rankine cycle) limitations, turbine alternator losses, condenser losses plus internal plant energy requirements. Hence the net sent out electrical energy of the power station (denoted kWhe) is some fraction of the heat rating of the fuel recovered in the boiler/reactor (denoted kWh). Table A2.3 is a comparison of Australian and US efficiencies from various power station types.

<table>
<thead>
<tr>
<th>Thermal efficiency</th>
<th>QLD</th>
<th>NSW</th>
<th>VIC</th>
<th>SA</th>
<th>WA</th>
<th>TAS</th>
<th>Aust ave</th>
<th>USA ave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>35.43%</td>
<td>34.27%</td>
<td>30.63%</td>
<td>30.38%</td>
<td>34.03%</td>
<td>32.95%</td>
<td>32.70%</td>
<td></td>
</tr>
<tr>
<td>Fuel oils</td>
<td>31.60%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural gas</td>
<td>36.80%</td>
<td>36.60%</td>
<td>31.06%</td>
<td>27.78%</td>
<td>30.80%</td>
<td>38.50%</td>
<td>33.59%</td>
<td>43.20%</td>
</tr>
<tr>
<td>Nuclear (fission)</td>
<td>36.80%</td>
<td>36.60%</td>
<td>31.06%</td>
<td>27.78%</td>
<td>30.80%</td>
<td>38.50%</td>
<td>33.59%</td>
<td>32.60%</td>
</tr>
</tbody>
</table>

Table A2.3 Thermal efficiency (heat rate) of Australian and US power stations 2012

Thermal efficiencies of some Australian fossil fuel power stations and their emission rates are

vii US Energy Information Administration [www.eia.gov](http://www.eia.gov)
comparable with those of the USA. Other factors are also shown in Table A2.4 which draws attention to one of the issues we might have to face i.e. the resistance to change re putting self-interests lower down the list of priorities. With vast investments in the up-to-date but still outdated fossil fuel industries there will be a tendency to maintain the status quo rather than opt for what is needed to be done for our younger and future generations. This may be one reason some politicians find it hard to accept the responsibilities that Climate Change presents. To quote Bill McKibben, (founder of the 350.org) from his book Eaarth, ‘The momentum of the [global] heating, and the momentum of the economy that powers it, can’t be turned off quickly enough to prevent hideous damage’.

Other large stationary CO\textsubscript{2} emitters include the cement and iron and steel industries but are much less potent in Australia than the plethora of fossil fuelled power stations currently in operation. There have been other methods proposed to reducing iron ore to iron other than in a blast furnace which reduce the amount of CO\textsubscript{2} released such as using a fluidised bed or even a microwave. Also a company called Zeobond in Melbourne produces E-Crete what they term as a geopolymer cement which does not require the calcification of limestone and so ‘reduces the embedded CO\textsubscript{2} content of concrete by 60% compared to ordinary Portland cement based concrete’. As well E-Crete uses recycled waste from power stations (fly ash) and iron and steel works (slag) as components.

The Alumina smelting industry is an intensive energy user and hence a potential greenhouse gas contributor if from fossil fuel generation. On average one tonne of aluminium production from ore takes 15.7 MWh of electricity (say 45 MWh of primary energy). An average humble can of beer or ‘Coke’ weighs 15 grams which would have taken 0.235 kWh of electricity or perhaps more importantly 0.67 kWh of fossil fuel energy complete with emissions to produce the basic material. Only about 5% of this energy is required to recycle aluminium so we need to recycle every can and any other scrap aluminium.
<table>
<thead>
<tr>
<th>Station</th>
<th>Type</th>
<th>Fuel</th>
<th>Registered capacity (MWe)</th>
<th>Thermalian efficiency (%)</th>
<th>Capacity factor 2012-13</th>
<th>Emissions tCO2e pa 2012-13</th>
<th>Emission kgCO2e/kWe</th>
<th>Emissions kgCO2e/kWhe 2013</th>
<th>AGL's Technical retirement</th>
<th>Owner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anglesea</td>
<td>Steam turbine</td>
<td>Brown coal</td>
<td>150</td>
<td>27.2</td>
<td>66.4%</td>
<td>1,097,521</td>
<td>1.1</td>
<td>0.953</td>
<td>2013.0</td>
<td>Alcoa</td>
</tr>
<tr>
<td>Barnsdale</td>
<td>OCGT</td>
<td>Natural gas</td>
<td>34</td>
<td>40.0</td>
<td>16.5%</td>
<td>755,000</td>
<td>0.5</td>
<td>0.943</td>
<td>2003.0</td>
<td>Sibley &amp; Brown Power</td>
</tr>
<tr>
<td>Hazelwood</td>
<td>Steam turbine</td>
<td>Brown coal</td>
<td>1600</td>
<td>22.0</td>
<td>31.3%</td>
<td>15,239,377</td>
<td>1.4</td>
<td>1.552</td>
<td>2002.0</td>
<td>GDF Surfest/CEA</td>
</tr>
<tr>
<td>Lake Macquarie A</td>
<td>OCGT</td>
<td>Natural gas</td>
<td>225</td>
<td>22.8</td>
<td>NA</td>
<td>26,949</td>
<td>1.1</td>
<td>3.89%</td>
<td>2003.0</td>
<td>FME/energy Australia</td>
</tr>
<tr>
<td>Lake Macquarie B</td>
<td>OCGT</td>
<td>Natural gas</td>
<td>256</td>
<td>22.8</td>
<td>NA</td>
<td>46,977</td>
<td>1.1</td>
<td>3.89%</td>
<td>2003.0</td>
<td>FME/energy Australia</td>
</tr>
<tr>
<td>Laverton North</td>
<td>OCGT</td>
<td>Natural gas</td>
<td>32</td>
<td>39.4</td>
<td>0.2%</td>
<td>14,957</td>
<td>10.1</td>
<td>0.698</td>
<td>2016.0</td>
<td>Snowy Hydro</td>
</tr>
<tr>
<td>Loy Yang A</td>
<td>Steam turbine</td>
<td>Brown coal</td>
<td>2120</td>
<td>27.2</td>
<td>37.5%</td>
<td>19,572,315</td>
<td>1.1</td>
<td>1.211</td>
<td>2006.0</td>
<td>GEAC</td>
</tr>
<tr>
<td>Loy Yang B</td>
<td>Steam turbine</td>
<td>Brown coal</td>
<td>10000</td>
<td>26.6</td>
<td>38.1%</td>
<td>9,16,002</td>
<td>1.1</td>
<td>1.236</td>
<td>2015.0</td>
<td>GDF Surfest/CEA</td>
</tr>
<tr>
<td>Mortlake</td>
<td>OCGT</td>
<td>Natural gas</td>
<td>500</td>
<td>30.0</td>
<td>35.5%</td>
<td>82,350</td>
<td>3.52</td>
<td>3.577</td>
<td>2005.0</td>
<td>Origin Energy</td>
</tr>
<tr>
<td>Newport</td>
<td>Steam turbine</td>
<td>Natural gas</td>
<td>500</td>
<td>33.3</td>
<td>4.2%</td>
<td>16,204</td>
<td>3.62</td>
<td>3.555</td>
<td>2003.0</td>
<td>FME/energy Australia</td>
</tr>
<tr>
<td>Somerton</td>
<td>OCGT</td>
<td>Natural gas</td>
<td>160</td>
<td>24.0</td>
<td>12.5%</td>
<td>13,635</td>
<td>0.85</td>
<td>0.77</td>
<td>2012.0</td>
<td>AGL Energy</td>
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<tr>
<td>Valley Power</td>
<td>OCGT</td>
<td>Natural gas</td>
<td>300</td>
<td>24.0</td>
<td>0.5%</td>
<td>12,779</td>
<td>1.09</td>
<td>0.77</td>
<td>2012.0</td>
<td>Snowy Hydro</td>
</tr>
<tr>
<td>Tallim</td>
<td>Steam turbine</td>
<td>Brown coal</td>
<td>480</td>
<td>23.5</td>
<td>34.3%</td>
<td>11,325,111</td>
<td>1.35</td>
<td>1.417</td>
<td>2005.0</td>
<td>Energy Australia</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Station</th>
<th>Type</th>
<th>Fuel</th>
<th>Registered capacity (MWe)</th>
<th>Thermalian efficiency (%)</th>
<th>Capacity factor 2012-13</th>
<th>Emissions tCO2e pa 2012-13</th>
<th>Emission kgCO2e/kWe</th>
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<td>2643</td>
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### Queensland (QLD)

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### South Australia (SA)

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<td>52,034</td>
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<td>0.537</td>
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<td>2024</td>
<td>Flio Energy</td>
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Page 188
Capacity factors were derived from the Clean Energy Regulator’s stated energy that a station actually generated in the year divided by the maximum possibly achievable itself derived from multiplying the registered capacity by the total hours in a year (i.e. MWh pa/(MW x 8760)). The capacity factor of a unit is dependent on, electricity demand, its generating cost, planned and unplanned maintenance. For a renewable energy unit like solar or wind it also depends on the relevant availability of the source of primary energy. The range of emissions in kg CO₂/kWh provides a comparison of the different fuels used plus the efficiencies of the units using the same fuel. Brown coal exhibits considerably more greenhouse gas discharge than black coal per unit of electricity generated which again emits considerably more than burning natural gas. Emission figures derived from the Clean Energy Regulator data varies slightly in some cases with that shown above by ACIL Allen but in the case of Energy Brix power station in Victoria Clean Energy figure works out at more than twice that shown above. The Technical Retirement date provided by ACIL is an indication of the capital write-off period yet to run. Investors will likely be reluctant to forego returns if the plants are shut down earlier. Alternately if and when regulation enforces CCS generating costs will increase considerably and 40% more energy and emissions will need to be catered for.
Appendix 5 – The Big Clean-up options

A5.1 Carbon Capture and Sequestration technology

Basically CCS is a method by which we could lessen the increase of greenhouse gas release into the atmosphere if we can capture some at 'birth'. It is then pressurised to somewhere between 6 and 18 MPa depending on the disposal site pressure and temperature. At these pressures the CO\(_2\) is in liquid form which ensures it is easier to transport and inject. To give some feeling for this a regular car tyre pressure is somewhere around 0.24 MPa and a BBQ gas bottle over a range of temperatures between zero and 54\(^\circ\) C will have an internal pressure of between 0.36 to 1.8 Mpa. 194

It is then transported by pipeline to a suitable site, sometimes up to several hundred kilometres and injected underground to depths varying between 800 and 4000 metres. The suitability of the site depends on several factors including its ability to be injected (sufficient rock porosity, fractures, permeability), its capacity (is it big enough?) and its integrity (will it leak?). The latter usually requires that the porous reservoir be capped with a substantially thick impervious rock to insure that the CO\(_2\), which tends to flow upward, will not escape and become imprisoned indefinitely. Deep saline reservoirs, depleted oil, gas and coal cavities are favoured. After commissioning the various sites require constant monitoring for leakage, seismic activity etc., long, long into the future.

Suitable sites:

As mentioned the suitability of a storage site depends on its integrity. A term used is 'injectivity', meaning the ease at which the CO\(_2\) can be injected regularly over the required period. Whether or not it has a thick, so called cap rock to act as a seal or it is permeable and of sufficient capacity for the anticipated burden and whether there are any seismic concerns, all have to pre determined. Proximity to the CO\(_2\) source is also a commercial consideration.

Much use has been made of CO\(_2\) to purge remaining oil and natural gas from wells to-date with the incentive of receiving a return. Disused oil and gas wells are favoured for their proven integrity. Saline aquifers (> 10,000 ppm salinities) provide another source where the CO\(_2\) is partially dissolved by the salty waters over time which increases the overall density and hence caused that CO\(_2\) to sinks to the bottom of the well. Otherwise the CO\(_2\) is less dense and tends to migrate upwards in an expanding plume.

Coal seams which are considered no longer suitable for mining have also been muted as suitable storage wells as the fractures in the coal seam provide considerable space. Deep ocean storage is also advocated by IPCC at depths of 1 km or more where it is said to be stably captured.

Capture:

CO\(_2\) as an unwanted by-product of industry such as natural gas enhancement, power generation, lime and cement plants, iron ore's reduction to iron in the steel industry and hydrogen production.
More often than not it is discharged to the atmosphere where it adds to the GHG burden. But if the particular industry is, for one reason or another, set on CCS the gas is first captured usually by the use of solvent amines in the gas waste stream which are basically ammonia modified hydrocarbons. It is a well-established technology, having been introduced sometime in the 1930s. The main choice in technologies appears to be monoethanolamine HOC₂H₄NH₂. When used in aqueous solutions at a low temperature it has the ability to extract CO₂ and hydrogen sulphide from a gas stream. When later it is heated it then releases the captured gases. The amine can be reused for a number of cycles.

Fig A5.1 Typical capture circuit

Other capture techniques are being trailed including membrane gas absorption where the membranes are sized to allow CO₂ to pass more readily than other molecules present in the stream and the use of solid adsorbents called zeolites, (a type of clay) which have the ability to attract CO₂ on their surface and release it again under higher temperatures and pressures. Both these are under trail regimes but potentially offer savings over the solvent methods in the future.

Fig A5.2 Cost effectiveness of technologies of separation Source: Feron 2010

The absorption process have the edge cost wise on separation of gases over membrane and adsorption methods
Transport:

To reduce transport costs the CO\textsubscript{2} is then cooled and pressurised to anything up to 18 MPa which depending on temperature is usually in a single dense (liquid) phase described as “something looking like WD40”. Entrained moisture is sometimes removed which allows the adoption of carbon steel pipework and the need for stainless steel. It is then pumped along say 200mm diameter pipe to the storage site wherever (sometimes hundreds of kilometres away) and injected deep underground.

![Phase changes in carbon dioxide](image)

**Fig. A5.3 the various phases of CO\textsubscript{2}**

For ease of transport and injection CO\textsubscript{2} is pressurised to a liquid phase at between 6 and 18 MPa.

Injection:

Injection of the liquid gas takes place up to 4 km underground depending on where the suitable strata lies in a steel lined bore several metres long which has a concrete jacket part way. CO\textsubscript{2} is known to corrode the concrete but some reports claim this forms a sealing type mud.

Monitoring:

Whether or not stringent international monitoring legislation will come into place soon, sound principles need to be established by all countries and participants and not just for the lifetime of the site's injection schedule. The storage sites need to be secure for hundreds and possibly a thousand years into the future to ensure the consignment does not break free. Down bore hole pressures and temperatures, 4D seismic recording, ground water analysis and surface gas detectors are all needed and to be made available to the public on-line or similar for as long as it takes.
Fig. A5.3 A typical well arrangement

Fig. A5.4 Pinpointed likely sites in USA
Fig. A5.5 Australia's possible sites. Courtesy of CO2CRC

Just how much of the Basins with potential for CO2 storage have been proven or even investigated is not readily available to the public except in the Gordon Basin (Bowen Island) and Bass Straight.
Appendix 6 - More on the big task

A6.1 Our Carbon Budget Calculations

From IPCC’s 2014 Summary for Policy Makers WG1 AR5 SFP Final we have the following statement:

- Limiting the warming caused by anthropogenic CO₂ emissions alone with a probability of >33%, >50%, and >66% to less than 2°C since the period 1861–1880², will require cumulative CO₂ emissions from all anthropogenic sources to stay between 0 and about 1570 GtC (5760 GtCO₂), 0 and about 1210 GtC (4440 GtCO₂), and 0 and about 1000 GtC (3670 GtCO₂) since that period, respectively. These upper amounts are reduced to about 900 GtC (3300 GtCO₂), 820 GtC (3010 GtCO₂), and 790 GtC (2900 GtCO₂), respectively, when accounting for non-CO₂ forcings as in RCP2.6.

We selected the reduced amounts therein to account for non-CO₂ forcings (e.g. methane, NOx etc.,) as in RCP2.6 to give us the greater than 66% chance of success having to limit emissions to 2,900 Gt CO₂ starting from the period 1861-1880. Subtracted the 1630, 1890 and 2150 Gt CO₂ emitted by the year 2011 we get the range of CO₂ emitted to that date i.e. worst, mean and best cases [a]).

We then compared available data on global CO₂ emissions for the period since 2011 plus their average rate of growth over the previous 10 years. While there are subtle differences between the various recordings we chose to use Carbon Budget's 2015 V1.1 spreadsheet as it was at the time, the most up to date.

It states the 2012 global emissions as 9.58 Gt Carbon for fossil fuel and cement manufacture and 0.97 Gt Carbon for land-use change emissions giving a total of 10.55 Gt Carbon. By multiplying by IPCC's conversion conversion factor of 3.664 this converts to 38.655 Gt CO₂.

b) Similarly total emissions for 2013 and 2014 add to 10.66 and 10.89 Gt Carbon respectively. So between 2011 and 2014 we have emitted 32.09 Gt Carbon. By multiplying by IPCC's conversion conversion factor of 3.664 this converts to 117.6 Gt CO₂. So the 3 scenarios as of 2014 would be as shown [b]).

The growth rate of emissions derived from that spreadsheet over the previous 10 years works out at 2.15% with the only negative growth taking place in 2008 and start of the Global Financial Crisis. So to extrapolate the 2014 figures to arrive at 2015 we subtracted the 2014 emissions inflated by 2.15% from the 2014 figures [c]). Similarly to arrive at the 2016 figure we subtracted the 2015 inflated emissions from the 2015 figure [d]). The 850 Gt CO₂ figure used throughout the document is a generous rounding off of the mean 2016 figure 846.

Extrapolating further using the business as usual road we have been travelling along it can be shown we will have exhausted our carbon budget by the years shown in [e])
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<th>Remaining (mean case) GtCO₂</th>
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<td>b)</td>
<td>2014</td>
<td>632</td>
<td>892</td>
<td>1,152</td>
</tr>
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<td>c)</td>
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<td>d)</td>
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<td>e)</td>
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<td>Best scenario</td>
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Appendix 10 – Transport in more detail

A10.1 Batteries

Flow batteries:

Flow batteries store the active materials, usually in two tanks, external to the actual battery cell. They are circulated through the cell via a pump at such a rate to meet the energy demand. They are essentially a rechargeable fuel cell. The first flow battery was developed in 1884 by Charles Renard to power his airship, La France. Interest in flow batteries was revived in the 1970s as a suitable energy storage facility and with the advent of variable renewables such as wind and solar. Considerable amount of research is taking place to produce commercially viable units.

Two major advantages over such as, Li ion batteries are:

1. the total amount of electrical energy they can deliver is a function of size of the tanks and
2. there is little degradation in performance over constant recycling.

Two major disadvantages so far are:

1. their complication with pumps, sensors, control functions and their overall power density although improvements in both are being hotly pursued in view of the potential market and
2. they tend to be large and would require scaling down with additional containment for use in most transport vehicles.

There is ongoing research into optimising the choice of materials, controls and the geometrics of flow batteries, particularly in the USA and Europe. Metals such as vanadium, zinc, titanium and compounds thereof plus totally organic materials and nanoparticles are all under review. Some are even combining technology and using lithium ion LiFePO$_4$ plus TiO$_2$ as electrolytes (Fig. A10.1)

It may seem difficult at present to imagine these ever rivalling Li-ion batteries for vehicular transport due to their size and complexity in the near future. What is clear is they are a serious contender as mass storage facilities at such as wind and solar power stations.

Fig. A10.1 One type of flow battery
Currently flow batteries tend to be large in size and need to have outer containment vessels in case of leakage of electrolytes. But presumably as development continues they could be scaled down to fit into transport vehicles.
## A11.1 Accidents

Fatalities:

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**Table A11.1 Nuclear fatalities** Courtesy: Wikipedia
A11.2 The fuel cycle

**Uranium:** Uranium is the main nuclear fission fuel. It is a silver grey metal with a density of 19.1 grams/cc, or 70% denser than lead. It is naturally radioactive, a legacy of the Big Bang. It has a half-life in the trillions of years range. As such it plays a major part in what is known as background radiation. Granite which forms a large part of the earth’s crust contains about 4 ppmg of uranium so background radiation in granite areas can be higher than other areas. It can also be present in coal which, when burnt, it can finish up in the atmosphere or ash deposits. Australia has around 29% of all uranium reserves, the largest portion in the world.

Uranium ejects an alpha particle to start off a very long radioactive decay chain which finishes as lead. It is made up of three natural isotopes 99.2745% $^{238}\text{U}$, 0.7200% $^{235}\text{U}$ and 0.0055% $^{234}\text{U}$. The only truly fissile isotope is $^{235}\text{U}$ therefore less than 1% of the original metal contributes to the energy generated in the large percentage of today’s reactors. More complete fission yield can be achieved in fast neutron reactors FNR by a process of converting the other uranium isotopes or thorium which are all fertile, by neutron absorption, into fissile materials. As Fig. 11.2 in Chapter 11 indicates there are only two FNRs still in operation as the others suffered operational challenges. The 250 MWe prototype fast reactor (PFR) at Dounreay in Scotland which finally shut down in 1994 only achieved a capacity factor of 26.9% over its 20 year operating life due to operational and maintenance issues.

The nuclear fuel cycle has several specific stages:
**Mining:**

Uranium is found in various concentrations throughout the world in an oxide form. It is contained in most soils, rocks, rivers and sea water to some degree. It is often mined along with other minerals. After dressing the extracted ore bearing earth the uranium oxide powder (U₃O₈ called Yellowcake due to its bright colour) and any other minerals are separated out and the tailings deposited usually in a tailings dam.

**Enrichment:**

Some reactors with high neutron economy can 'burn' natural uranium i.e. uranium with the same ratios of isotopes as listed above. The now retired MAGNOX reactors used natural uranium metal clad in a magnesium alloy, hence the name. CANDU PHWR reactors have a range of uranium fuels including natural uranium as an oxide UO₂. They can also be adapted to use so called enriched the fissile (i.e. in ²³⁵U) isotope as well as reprocessed spent LWR fuel which normally has a slightly higher fissile component than natural uranium. But most reactors in operation today use uranium oxide fuel enriched in the fissile isotope from anywhere between 0.9 to 5% with some research reactor's enrichment being much higher.

The original method of enriching uranium was developed in the USA and involved the diffusion process. It is now deemed an obsolete gave way to the newer centrifuge process. Both enrichment chains adopted uranium hexafluoride (UF₆) as the medium which is a solid white crystal at room temperature but vaporises to a gas at 56.9 °C. The diffusion process used thousands of chambers linked in series each having a semi porous membrane which allowed the pressurised uranium hexafluoride to separate slightly into higher and lower concentrations of the fissile and fertile components. The higher up the chain of chambers the higher the fissile component became. Centrifuge process again uses thousands of centrifuges linked in series but instead of the diffusion to separate the isotope centrifugal force to cause the heavier ²³⁸U to migrate to the outer radius leaving the enriched UF₆ to be withdrawn from the centre much like the operation of an industrial separation cyclone, and to be transferred upstream.

There are several other techniques, mainly refinements on the centrifuge but the bulk of enriched uranium is currently produced by the standard centrifuge process.

The cost of enrichment is based on the amount of work that has to be expended on reaching the required product enrichment UF₆ from the 'natural' UF₆ called a separative work unit (SWU). Charges are made per kg SWU or sometimes tonne SWU.

There are several centrifuge enrichment plants around the world including USA, Russia, France, China and Japan. The one with the largest capacity SWU pa is a joint German/Netherlands/UK facility in Capenhurst, UK. Clearly security is a prime issue and the main reason for issues with Iran's nuclear ambitions.

A nuclear power station with a capacity of say 1,300 MW may require an annual charge of about 25 tonnes of enriched uranium with a concentration of 3.75% fissile ²³⁵U. This quantity would be produced from about 210 t of natural uranium using about 120 t of separative work (120t SWUs). The amount of SWU is dependant on the feedstock and waste product fissile ²³⁵U characteristics. This example would result in a waste assay of around 0.31% fissile ²³⁵U. But a nuclear utility operator whose reactor core requires enriched uranium feedstock is entitled to define what the tails assay (how much fissile ²³⁵U remains in the waste product). In the case of say a CANDU PHWR reactor operator using spent PWR fuel as enrichment feedstock of say 1% fissile ²³⁵U to produce 20 tonnes of recharge fuel with an assay of say 3% fissile ²³⁵U may also chose the waste assay to be say 0.2% fissile ²³⁵U. The result would be require a feedstock of 70 tonnes of uranium feedstock as UF₆ and approximately 60 tonnes SWUs and a decision could be made too
proceed depending on whether the final enrichment cost is economically viable for them.

As you can imagine the stockpile of depleted uranium (waste) is large. Around 1.5 million tonnes to date and growing at around 50,000 tonnes pa.\(^{197}\) It is relatively safe having a low energy alpha radiation characteristics but can be, much like lead, when vaporised any fumes can be ingested.

It is used as radiation shielding, with a fine coating of inert metal to attenuate the alpha radiation, as its density makes it much superior to that of lead. It is also used to de-enrich weapons grade uranium when political opportunities permit. It can be mixed with plutonium to form mixed oxide reactor fuels (MOX) and could be used as fertile material in the blanket of a FNR to breed plutonium \(^{239}\)Pu fuel.

But on a more sinister side it has been used for armour piercing weapons again due to its high density and on impact about 30% of resulting vapour will bust into flames.

The Australian Nuclear Science and Technology (ANSTO) has developed a laser process of enrichment called SILEX which shows great promise and is currently being trialled by licensees GE-Hitachi in the USA.

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**Fig. A11.1:** A schematic diagram of a typical nuclear fuel cycle. Courtesy: European Nuclear Society

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**Fuel fabrication:**

Whether the type of reactor requires natural or enriched uranium the feedstock (\(\text{U}_3\text{O}_8\) or \(\text{UF}_6\) respectively) is usually converted to \(\text{UO}_2\) and pelletised and several pellets are encased in a tube of
low neutron absorbing metal such as zirconium. Several tubes are then assembled into a metal frame assembly also of low neutron absorbing material.

LWR are usually shut down and refuelled once a year or maybe longer with the spent fuel assemblies representing say one third of the centre of the core are replaced by adjacent outer ring of partially spent fuel assemblies while these in turn are replaced by the new fuel assemblies.

Such as CANDU PHWR reactors are usually continuously refuelled with new fuel rods being inserted into one end of the reactor core to discharge the spent fuel at the other end.

Fig. A11.2 Exploded view of a PWR fuel assembly. Courtesy: World Nuclear Association

| Individual fuel assembly typically have a tube matrix 17 x 17 in a frame with a cross section of 20 x 20 cm. Most tubes are fuel tubes but some are designated for control rod placement. The overall fuel assembly can be up to 4 m long and weigh half a tonne. There are typically 193 assemblies in a 1000MW reactor core. BWR assemblies are not dissimilar. |
Reprocessing:

Perhaps the most complex part of the fuel cycle is reprocessing. President Jimmy Carter proclaimed in 1977 that the USA would not reprocess their nuclear fuels due to the perceived issues that it was both expensive and would lead to security issues should a rogue entity get hold of the fissile materials, especially $^{239}$Pu. Instead it was proclaimed that the assemblies should be stored safely deep underground for indefinitely. This is still the case and so far the USA has 70,000 tonnes buried under a mountain in Nevada$^{198}$. Ironically the spent fuel from LWRs, as well as having $^{239}$Pu present also has a high proportion of $^{240}$Pu content, which can spontaneously fission (fission independent of any neutron or other absorption) making any weapons using such recovered plutonium presenting a high risk of pre ignition.

Most of the rest of the nuclear world however does recycle which significantly reduces the amount of waste to be encased and stored underground as the large proportion is made up of $^{238}$U. Reprocessing plants for commercial applications are located in France, UK, Russia, Japan and India. Some 90,000 tonnes of spent fuel has so far been reprocessed and is carried out remotely due to the high radiation levels.

After slicing up the fuel assemblies they are dissolved in hot, concentrated nitric acid. Most reprocessing plant also use a system called PUREX (plutonium and uranium extraction) which effectively separates out the plutonium and uranium from the fission products. Both elements can then be returned to the fuel cycle. The remaining 3% or so is made up of highly radioactive isotopes and actinides. This is dried and encapsulated in borosilicate glass ready for long term underground storage$^{199}$. In terms of waste site volume the space required is around 38% of that needed if no reprocessing takes place.

Australia has developed a hard rock type radioactive waste encapsulation system called Synroc which is gaining considerable interest world wide.
**Waste storage:**

Nuclear waste storage is probably the most controversial aspect of the industry. As recently witnessed in Australia the Federal Government's proposals to establish a waste site somewhere in the country, with several nominated locations as a possible site, has met with a strong wave of public resistance and NIMBY outcry. Similarly in the USA some states have put a ban on building any new nuclear plants until some commitment is made to recycle their spent fuel. One counter argument suggests that if Australia is prepared to export its uranium, as Australia does, shouldn't it be prepared to recover the spent fuel both for security and radioactive waste disposal?

Deep geological sites at least 1 km or deeper need to be in solid, dense stable rock with low levels of ground water movement to prevent threats to water supplies. There should be low seismic conditions and no volcanic activity and located remotely from human habitation. Depleted salt mines are often chosen.

Additional sealing of walls with concrete may be needed.

![Fig. A11.4 A typical reactor waste depository. Courtesy: Nuclear Tidings.](image)

**A11.3 Waste production comparison – nuclear vs fossil power stations**

Based on the figures given above, the 25 tonnes of spent fuel extracted say each 12 months for a 1,300MW would amount to 0.75 tonnes of radioactive waste to be buried. Over a 35 year life span that amounts to less than 27 tonnes. Within 20 years spent PWR fuel for example, radiation levels will have decade to around 7% of its original radioactivity. GHG emissions would be limited to such as transport services. The waste is a solid and sealed, usually in a vitrified ceramic.

Comparing this with say a 1,300 MW coal fired fuel power station also with an economic life of 35 years, a capacity factor of 80% and a thermal efficiency of 36% using average NSW thermal coal data of LCV 6.83 KWh/kg, a carbon content of 60.8%, an ash content of 21.6%, an arsenic content of 3mg/kg coal and a beryllium content of 3.9 mg/kg coal, a mercury content of 0.065 mg/kg, over its lifetime there would be almost 289 million tonnes of CO$_2$ emitted and over
28 million tonnes of ash, the latter of which would contain a cocktail made up of 389 tonnes of arsenic, over 500 tonnes of beryllium and 8 tonnes of mercury. And if this fuel is similar to Australia's export coal, this ash may also include 285 tonnes of uranium$^{235}$ and 480 tonnes of thorium.$^{201}$ $^{202}$ $^{203}$ Hopefully it is all kept well away from the ground water.

If it adopted CCS to the coal fired plant, the liquefied CO$_2$ gas finally stored underground, and of infinitely greater quantity than the nuclear plant's waste, would rely on the integrity of the surrounding geological structure to keep it from escaping. The electrical energy from the power station actually exported to the grid would be reduced by around 40%.

A11.3: The Periodic Table

![Periodic Table of Elements](image)

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

Table A11.2: The Periodic table of elements Courtesy: Ptable

A11.4 Background radiation

We are all exposed to natural background radiation as a feature of our planet. Mankind however is adding to this as is depicted in Fig. A11.4. ANSTO advise Australians receive about 1.5 - 2.0 'millisieverts' of ionising radiation every year. This is natural background radiation. Low exposure to ionising radiation is not harmful$^{204}$. In comparison a typical X-ray/CAT scan of your head could expose you to 2.6 millisieverts. A sievert is a measurement of equivalent dose and effective dose.
Fig. A11.4 contributions to background radiation. Courtesy: passmyexams.co.uk
Appendix 12 – Nuclear Fusion in more detail

A12.1 Coulomb barrier

Like charges repel and unlike charges attract. Charles Augustin de Coulomb (1736 to 1806) determined the property of electrostatic interaction between any two charged nuclei. It became known as the Coulomb Law. It refers to the force needed to allow the nuclei to approach close enough to meet up. It follows the inverse square law and its relationship is:

\[ F = \frac{kZ_1 Z_2}{r^2} \]

where \( F \) is the force in Newtons, \( k \) is the Coulomb constant which varies depending on the medium the nuclei are suspended in e.g. air, water, vacuum etc., but is usually taken as equal to \( 9 \times 10^9 \) Nm\(^2\)/C\(^2\). \( Z_1 \) and \( Z_2 \) represent the number of protons and hence the respective charges on the two nuclei in Coulombs (i.e. amperes x seconds), \( r \) is the distance between the two nuclei in metres. It is a very powerful repulsive force however of much less magnitude than the attractive strong nuclear force but with its much shorter range. If certain conditions prevail the strong nuclear force, can overcome its rival such as very high velocities (temperature) of the protons.

This being the result then the time factor (dwell time \( T \)) plays a major part as to whether fusion of the two nuclei takes place or not.

For the fusion event to be self-sustaining depends on the probability of many such fusions taking place at the same time. This will be determined by the density of such nuclei \( \tau \) (nuclei per m\(^3\)).

Theoretical values of required temperatures to overcome the Coulomb barrier can be calculated from the equation:

\[ \text{Kinetic energy of the nuclei} = \frac{1}{2} m v^2 = \frac{3}{2} k_b T \]

where \( k_b \) is the Boltzmann’s constant. If the kinetic energy relating to where the height of the Coulomb barrier equals the depth of the strong nuclear force is determined the theoretical value of \( T \) for fusion of two protons in free space can be found at a staggering 40 billion °K. But this is far hotter than the centre of the sun at around 15 million °K, so we know there must be short cuts.

Thankfully this appears to be experienced in fusion research here on earth also. In fact there are two phenomena which possibly provide explanations for lower fusion temperatures as follows:

Maxwellian distribution. The formula calculates the average Coulomb force to be overcome per proton required for fusion. The proton containing nuclei in the fast end tail of their bell curve energy distribution can be in sufficient numbers to do the job on their own. (Fig. A12.1)

Quantum mechanics tunnelling, provided there is not too much of a gap between the height of the Coulomb force and the depth of the strong nuclear force, can provide a 'tunnel' for the nuclei well below the peak.
A12.2 Positrons & neutrinos

A positron is a sub atomic antimatter particle of the same mass \((9.109 \times 10^{-13} \text{ kg})\) but opposite charge of an electron. The theory of the presence of antimatter was postulated back in 1928 by a mathematician called P. A. M. Dirac long before any such phenomena were discovered. They are formed by the fusion of protium \((\overset{1}{1}\text{H})\) in stars including our sun. They can also be generated along with an electron when a photon of gamma radiation strikes a nucleus of some element and is a principle used in gamma ray shielding. As soon as a positron strikes an electron they annihilate one other.\(^{206}\)

A neutrino is another subatomic phenomena which has virtually zero mass and no charge. Again its existence was postulated in 1931 by Wolfgang Pauli before it was discovered in 1959 by Clyde Cowan et al. The name means ‘little neutral one’ coined by Enrico Fermi.

Billions of these neutrinos pass right through our bodies from outer space every second. There are three types (called electron, muon and tau) which are least understood of practically any sub atomic entity and currently attracting considerable scientific research.\(^{207}\)

A12.3 Superconducting magnets

Some materials when cooled to almost absolute zero \((0 \, \text{K or} -273 \, °\text{C})\) display extremely high magnetic fields and almost zero electrical excitation. This of course makes their use desirable in many scientific and technical operations including many fusion experiments. There are several alloys that can be used but the main ones to be used in ITER fusion reactor are Niobium-Tin \((\text{Nb}_{3}\text{Sn})\) or Niobium-Titanium \((\text{Nb}_{3}\text{Ti})\). The former are used in the central solenoid and toroidal field coils while the later are used in the poloidal field coils and will operate at 4 °K facilitated by supercritical cryogenic systems. The series of fine filament windings are suspended in a glass-polyimide insulation material. \(^{208}\)They can be damaged if the current and/or field is increased indiscriminately when the resistance will increase causing the magnet to heat up rapidly. As with all such components detailed specifications of operating properties are of paramount importance to the
equipment designer.

A12.4 Temperature measurement

Clearly at the temperatures of operating fusion reactors usual run of the mill thermocouples or thermometers are impractical. What is normally used in such circumstances is a property known as the optical emissions of line radiation of excited nuclei or atoms using very sophisticated cameras. When such a particle travelling at speed experiences a transition in energy state such as suddenly being slowed down by impact by another it will shed photons of one or more energies specific to the element in question. Light photons being given off can be displayed as a series of lines. Typical photon spectrum from a sodium lamp is shown in Fig. A12.2. The spectral width of the lines tell a story and if the energy level of the sodium is reduced in some fashion the thickness of the lines reflect the degree of the reduction.

![Spectrographic display of a high pressure sodium lamp spectrum](image)

In a fusion reactor if neutral deuterium is injected into the plasma there is a possibility that a resulting $^4$He nuclei may capture an electron from the deuterium and be able to radiate a spectrum which, if captured in a spectrograph, will indicate the temperature of the helium (from measuring the line widths) as well as the density (from the intensity).  

(1 MeV = 4.405 x 10^{-20} kWh or can also be expressed as 1.1604 x 10^{10} °K when Boltzmann’s constant is taken into account)
Reno NV - 25th June 2008
169 A New Approach to Fusion – A startup snags funding to start early work on a low-budget test reactor. - Tyler Hamilton – MIT
Technology Review - 31th June 2008
170 Compact Toroid Injection Experiment (CTIX) – UCDavis http://ctix.ucdavis.edu/ct_explain.html
172 Development of Merged Compact Toroids for Use as a Magnetised Target Fusion Plasma – S Howard et al presented at ICC 2008
173 Polywell Fusion – Electrostatic Fusion in a Magnetic Cusp – Jaeyoung Park – EMC2 – Fusion Power Associated Meeting
174 Plasma focus- The machine - http://web.brasimone.enea.it/plasma/plasma1.htm
177 Exclusive: Secretive fusion company claims reactor breakthrough – Daniel Clery Science AAAS News 24th August 2015
178 MHD Activity in an Extremely High-Beta Compact Toroid – Tomohiko Asia and Tsutomu Takahashi – Nihon University – Japan
180 Sustainable energy - without the hot air. Version 3.5.2 Prof. David MacKay Nov 2008
182 Sherwood et al A Drier Future, Science Feb 2014 Vol 343 p 737
183 IIAS Working paper WP-75-063 – Can we control carbon dioxide- Nordhaus W D 1975
185 2-Degree Global Warming Limit is Called a 'Prescription for Disaster' – Mark Fischetti Scientific American 6th Dec 2011
186 Climate policy: Ditch the 2° C warming goal – Nature 1st Oct 2014 DH Victor & C F Kennel
187 The NOAA Annual Greenhouse Gas Index (AGGI) – NOAA Earth Research Laboratory – J H Butler & S A Montzka
188 Cape Grim CO2 data – CSIRO 2014 spreadsheet
189 Climate Change 2007: Synthesis report Fig 2.4 page 39
190 Basic information - Natural Gas Star Program – US EPA updated 26th Feb 2016
197 Uranium and Depleted Uranium – World Nuclear Organisation
199 Processing of Used Nuclear Fuel - World Nuclear Organisation – Nov 2015
201 Uranium in Australian export thermal coals – CSIRO Fact sheet
202 Coal ash is more radio active than nuclear waste – Mara Hvistendahl Scientific American - 13th Dec 2007
203 Thorium in Australian export thermal coals – CSIRO Fact sheet
204 Natural background radiation – ANSTO
205 Hyperphysics - http://hyperphysics.phy-astr.gsu.edu/hbase/electric/elefor.html
206 Neutrino – Wikipedia
207 ITER The way to new energy – Magnets - http://www.iter.org/mach/magnets
208 Measuring ion temperatures and helium densities in the hot core of a nuclear fusion reactor using sCOM and EMCCD cameras – Andor Technology Plc