



# BACKGROUND PAPER ON SOLAR CONVERSION OF BROWN COAL

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December 2012





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### **Background paper on solar conversion of brown coal**

**December 2012**

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### **About IT Power**

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## Summary

At the present time, oil accounts for over 30% of world primary energy and gas a further 20%. In terms of the financial value invested in delivering that primary energy to the point of use, oil accounts for nearly 70% of cash flows, reflecting its higher value.

Energy Type	2012 Market value \$/GJ
Black coal (export)	3.4
Oil and oil products	18
LNG (export)	7.3
Uranium (export)	0.2
Brown coal	0.7
Natural gas Eastern states	6.0
Waste Bagasse	0.8
Conc. Solar Radiation	7.5

Fluid fuels offer the advantages of high energy density, ease of transport and storage and high efficiency in conversion to work. They are likely to maintain an important role for a long time, if not indefinitely, into the future. The choice of the dominant fluid fuel may well change over time.

Gasification processes are a key enabling step towards a range of future conversion approaches for brown coal. They provide for higher efficiency power conversion via combined cycle systems, offer the possibility of pre-combustion CO<sub>2</sub> capture and are also the starting point for production of liquids for oil replacement. Direct conversion of coal to liquids is also

possible.

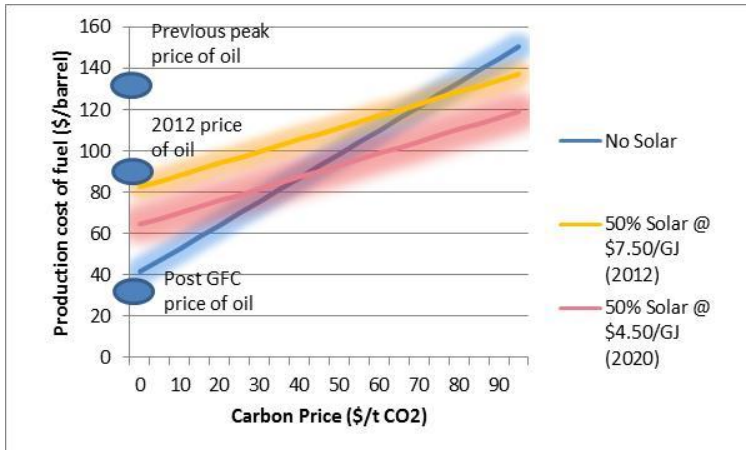
Concentrating Solar Thermal technologies use arrangements of mirrors to focus Direct Beam solar radiation to receivers where high temperatures can be produced. There is a strong emerging industry using concentrated solar for power production. Directly driving thermochemical reactions with concentrated radiation is a new application.

This scoping study examines the technical and economic plausibility of the various options for combining brown coal and concentrated solar, via a literature review and high level analysis.

Possible approaches identified include:

- Use of solar process heat.
- Low temperature supercritical water gasification of brown coal in a linear concentrator.
- Direct coal to liquids reactions in a linear concentrator.
- Gasification within a high temperature solar heated molten salt tank.
- High temperature super critical water gasification using a tower or dish concentrator.
- Entrained flow or fluidised bed gasification using a tower concentrator.

Based on the uncertain cost data available, it appears that standard coal to liquids processes would be quite profitable at current prices for oil, but face an uncertain future carbon price situation. Solar driven conversion of coal to liquids appears just viable even with current costs of solar. Solar cost is projected to fall strongly over time so the potential return on investment should improve. A solar driven process also has the advantage of lowering the carbon dioxide emissions intensity down to a point slightly less than conventional oil. The result is that with likely 2020 solar costs, the carbon price at which it would be more cost effective than a non-solar process could fall



anywhere between \$10/t and \$70/t. Choice of the solar option has the effect of largely removing the investment uncertainty associated with an unknown future price on CO<sub>2</sub>.

Converting brown coal to gas for sale or for power generation only appears marginally competitive with natural gas prices of \$6/GJ and increasingly un-competitive with carbon pricing. Solar driven gasification does not

appear to help this situation.

If efficient heat recovery from reactant streams is used for power generation in parallel with liquids production, then the effect is to significantly improve economic performance. If such power generation could earn renewable energy certificates the effect could be to lower the break even sale price for liquids by as much as \$30/ barrel.

Where available brown coal resources do not coincide with good solar resources, it appears that the cost of transporting coal is sufficiently low that taking coal to a high solar site would be more cost effective than processing it at a low solar site.

Given the positive findings from this initial scoping study, a more detailed feasibility study of technical options and costs is recommended. Noting that the solar driven processes needed are still in the R&D phase, it is suggested that those aspects would be worth further investment to prove them in pilot scale.



# 1. INTRODUCTION

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Brown coal is characterised by a higher ratio of hydrogen to carbon than high rank coal together with higher moisture levels. In conventional steam based power generation, the higher moisture content leads to a lower conversion efficiency and hence higher average levels of CO<sub>2</sub> emissions than black coal. Interest in reducing emissions intensity of use also coincides with a generally increasing global price of oil and a decline in Australia's domestic production of oil.

Gasification processes are a key enabling step towards a range of future conversion approaches. They provide for higher efficiency power conversion via combined cycle systems, offer the possibility of pre-combustion CO<sub>2</sub> capture and are also the starting point for production of Fischer Tropsch liquids for oil replacement. Direct conversion of coal to liquids is also possible. In the context of gasification / chemical conversion, the high moisture content and high reactivity of brown coal can be turned to advantage.

In conventional approaches to gasification, a fraction of the coal is oxidised to provide the energy input to drive the overall endothermic reaction. Concentrating solar thermal technologies have been demonstrated to directly drive a range of high temperature endothermic reactions. Combining input from brown coal technologies and concentrating solar may offer an overall systems approach that could be "better than the sum of its parts", and may offer a route to reduced CO<sub>2</sub> emissions.

Brown Coal Innovation Australia (BCIA<sup>1</sup>) is a not-for-profit company with a mandate to co-invest with stakeholders in brown coal innovation and emissions reduction technologies. BCIA has commissioned this initial scoping study to provide a reality check on the various options for combining brown coal and solar, using a literature review and high level analysis. This study aims to:

- Clarify and pose the most immediate further questions for consideration.
- Inform BCIA's potential involvement in road-mapping investigations of solar fuels (such as the ASI funded investigation by CSIRO).
- Provide background information to support future consideration of investment in R&D activities around solar driven gasification.

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<sup>1</sup> <http://www.bcinnovation.com.au>

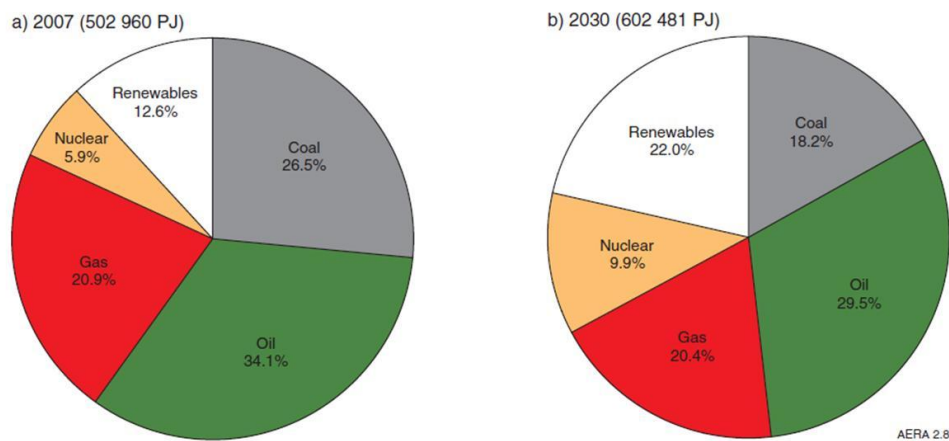


## 2. THE FUTURE OF FUELS

In considering the role of solar conversion of brown coal, an essential context is the future evolution of the world market for liquid and gaseous fuels. Appendix B assembles and reviews material relevant to both the global and Australian situations in addition to the discussion here.

Figure 1 shows the present breakdown of traded primary energy globally together with the IEA's prediction for 2030. At the present time, oil accounts for over 30% of world primary energy and gas a further 20%. In terms of the financial value invested in delivering that primary energy to the point of use, oil accounts for nearly 70% of cash flows, reflecting its higher value, and gas a further 17%.

Arguably the world is at a point of change in its energy supply and use patterns so forward projections that rely on extrapolation of historical trends could easily prove wrong.



**Figure 1: Outlook for world primary energy demand, based on IEA data, reproduced from ABARE (2010)**

Rapid changes in energy supply that are currently being experienced and seem certain to continue are driven by among other factors:

- High levels of concern around climate change caused by anthropogenic Greenhouse Gas Emissions.
- A peak in production of “conventional oil”.
- Continued high growth in energy demand in developing economies, particularly India and China.
- Very strong growth in renewable energies (particularly wind and solar PV), with very strong pro-active efforts from China, in particular, to achieve a dominant position in the new technologies.





In contemplating future energy mixes, analysts typically focus on end use energy, with stationary energy and transport being the main driving sectors. In attempting to predict the future roles and shares of technologies and fuels it is also vital to consider the impact of energy transfer between countries.

Stationary energy is almost synonymous with electricity and seems certain to remain so. However the supply mix for electricity generation is likely to continue to evolve quite rapidly. Moves to lower emissions of greenhouse gases (GHG) seem most likely to continue in general, irrespective of sudden changes of direction in policy within different levels of government in different countries and at different times. Growth in wind and solar photovoltaic (PV) seems highly likely to continue however limits to the level of variable / non dispatchable supply that the system can take will be tested. Household / customer level generation and demand management seem likely to increase. Renewable energies with storage, and high efficiency conversion of fuels by combined cycle systems or fuel cells seem highly likely to receive increased attention.

The future of transport energy is harder to predict. A comprehensive study by CSIRO (Graham et al 2008) on the future of transport in Australia is relevant, it is discussed further in Appendix B. Some argue for an almost complete trend towards electrification. At least a significant trend towards electric vehicles is likely, however using combustible liquid fuels has enormous advantages. The energy density by volume or mass including the containment is many times higher than other forms of energy other than nuclear fuel. Handling by pumping, piping and storage vessel is convenient and low cost. The speed of re-fuelling transport vehicles is high. Batteries remain expensive and of low per unit mass energy density. It could be that fuel cell enabled vehicles will have a role in combining the advantages of both approaches.

The role of energy transfer between countries gets less discussion. However it is essential to mapping out the global energy future. There are many major centres of economic activity which can not be energy self-sufficient under any realistic scenario. Japan and Singapore are extremely relevant examples in the Asian region with strong trade links to Australia. At present the bulk of energy transfer between economies both in energy and even more so in financial terms, is oil. Coal is very significant and liquified natural gas (LNG) is a growth sector. There is discussion of global "super grids for electricity" taking on the energy transfer role. In Europe, connection of the Mediterranean region to North Africa and Middle East (Desertec 2009) to share renewable energy resources, makes a lot of technical sense. Issues around political stability however make it challenging. However the costs of energy transport both in energy cost and financial cost are of the order of ten times higher via transmission line compared to shipping oil or other fuels.

In this context fluid fuels seem highly likely to maintain an important role for quite some time or even indefinitely into the future. The choice of the dominant fluid fuel may well change over time however. Possibilities include:

- Hydrogen (H<sub>2</sub>); has been the subject of much promotion and anticipation over many decades. It has the advantage of combustion to pure water. It's major disadvantage is that it is extremely difficult to achieve a practical volumetric or mass based energy density for storage or transport. It can be produced from fossil fuels or splitting of water.

- Methane ( $\text{CH}_4$ ); is the main constituent of natural gas. Liquefaction is costly but practical and now proven for international trade. Methane can be synthesised from other sources such as coal or biomass.
- Methanol ( $\text{CH}_3\text{OH}$ ); is the simplest hydrocarbon liquid, it can be synthesised from base sources such as natural gas or coal or biomass, and it is more convenient for use and transport than methane. It is however carcinogenic and has a lower energy density than current oil based fuels.
- DME Di Methyl Ether ( $\text{CH}_3\text{OCH}_3$ ); requires a slightly elevated pressure to maintain as a liquid (similar to LPG). It has no carcinogenic concerns. It can be used for transport relatively easily. It is synthesised from Methanol.
- Ammonia ( $\text{NH}_3$ ); there is a strong body of R&D establishing the practicality of ammonia as a liquid fuel. It must be kept at slightly elevated pressure to be maintained as a liquid. A large spill is a Caustic / cryogenic hazard, but it is otherwise non toxic. It can be seen as a practical liquid vector for use of hydrogen since it is made from hydrogen combined with nitrogen from the air.
- Synthesised “Drop in fuels”; synthesis of fuels that meet existing standards for diesel, gasoline and aviation fuels have the advantage that the existing infrastructure and market place can continue seamlessly. In terms of inherent desirability, diesel in particular has a lot of benefits. They can be synthesised from coal, natural gas or biomass or any other source of hydrogen and carbon.

Of these various options, there is a dichotomy between those that contain carbon and those that don't. If the carbon in a fuel originates from biomass then nature provides a closed cycle. If the carbon originates from a fossil fuel, then combustion will release  $\text{CO}_2$  with greater or lesser intensity depending on the processes of producing and using the fuel. If the  $\text{CO}_2$  is captured at the point of combustion, it could either be sequestered or in principle returned for recycling.

## 2.1. Relative market values of energy types

The various forms of energy in economic use are typically discussed in terms of their own traditional units of energy that have arisen from their historical evolution. This has the unfortunate consequence of making it hard to compare different energy types directly in common discourse. Appendix A reproduces a number of energy conversions and definitions relevant to this discussion. Table 1 attempts to show the value per unit energy of different types of energy in current terms using a range of energy units. The units of \$/GJ represent the most appropriate SI units and provide a basis for comparing the various energy types on an equal basis.

Amongst other observations, it can be seen that oil is approximately 2.5 x more valuable per unit energy than gas, 5.2 x more valuable than exported black coal and 25 x more valuable than brown coal or waste biomass. In turn, diesel before excise is 1.45 x the price of imported oil. Retail electricity on the other hand is 1.2 x more expensive per unit energy than retail diesel. The



current financial incentive for a shift to electric transport is not from the cost of the energy but because efficiency per distance travelled is around 3 times higher.

**Table 1: The relative value per unit energy of different energy types in Australia using several alternative energy units, highlighted cells indicate units in most common use.**

Energy Type	\$/GJ	\$/MWh	\$/barrel oil equiv. @ 6.1GJ/bbl	\$/litre diesel equiv. @ 39MJ/l	Source of data
Black coal (export)	3.40		20.7	0.13	ABARE (2010) Import, Export stats
Oil and oil products	17.88		109.1	0.70	ABARE (2010) Import, Export stats
LNG (export)	7.30		44.5	0.28	ABARE (2010) Import, Export stats
Uranium (export)	0.19		1.1	0.01	ABARE (2010) Import, Export stats
Brown coal	0.70		4.3	0.03	BREE (2012) AETA fuel costs quoting Acil Tas medium
Brown coal + \$23/t CO <sub>2e</sub>	2.70		16.5	0.11	
Black coal	2.20		13.4	0.09	BREE (2012) AETA fuel costs quoting Acil Tas medium
Black coal +\$23/t CO <sub>2e</sub>	4.20		25.6	0.16	
Natural gas Eastern	6.00		36.6	0.23	BREE (2012) AETA fuel costs quoting Acil Tas medium
Bagasse East	0.80		4.9	0.03	BREE (2012) AETA fuel costs quoting Acil Tas medium
Nuclear	0.75		4.6	0.03	BREE (2012) AETA fuel costs quoting Acil Tas medium
Diesel TGP	35.90		219.0	1.40	AIP (2012) Terminal Gate Price
Diesel excise free	26.03		158.8	1.02	TGP - 38.5c/litre
Wholesale electricity	11.94	43	72.9	0.47	Indicative estimate
Retail electricity	44.44	160	271.1	1.73	Indicative estimate
Conc. Solar Radiation	7.50	27	45.8	0.29	CSP in Australia analysis, Lovegrove et al (2012)
Conc. Solar heat (in HTF)	10.83	39	66.1	0.42	CSP in Australia analysis, Lovegrove et al (2012)
CST electricity	69.44	250	423.6	2.71	CSP in Australia analysis, Lovegrove et al (2012)

These relative values, illustrate a strong financial incentive to seek cost effective technology approaches to convert the lower priced energy sources such as brown coal and biomass to forms that can command the higher prices of oil or diesel / gasoline.

Three values for concentrated solar energy are listed at the end. All are levelised costs, amortising cost of systems and O&M (based on Lovegrove et al (2012)). A value of \$7.50/GJ for concentrated solar radiation represents the levelised cost of energy delivered as focussed high

intensity radiation before conversion. The value of \$10.83/GJ corresponds to heat in a process stream to a central plant and the highest value of \$69/GJ applies after conversion to electricity.

These are estimated Australian 2012 values, projected to reduce to around half that value by 2020 or 2025.

The value of concentrated solar radiation at \$7.50/GJ is considerably higher than the value of brown coal energy but still considerably less than that of oil. It suggests that on initial simple economic terms, there is no case for simply saving brown coal energy via use of solar. On the other hand if the process of converting the solar energy, actually includes a processing step for the brown coal, (ie there is a substitution of capital costs), there could well be potential, particularly if a cost of carbon or other environmental considerations are considered.



### 3. CONVERSION OF BROWN COAL

Brown coal is a solid hydrocarbon usually with a high level of water trapped in its structure, the characteristics and composition of Brown Coal are summarised in Appendix C. There are a complex range of possibilities for transforming and using a solid hydrocarbon such as brown coal. Essentially any hydrocarbon can be broken down into smaller building blocks via the application of heat, usually together with  $H_2O$  or  $CO_2$ . Smaller hydrocarbons can be assembled to make larger hydrocarbons usually with a smaller amount of heat given off. Thus any hydrocarbon can in principle be made into any other desired hydrocarbon.

The fundamental tools / principles which chemical engineer's have at their disposal to design processes for such transformations include:

- For any given input mix, a particular temperature and pressure will result in a particular final "equilibrium" composition of products.
- Different reactions proceed at different rates and can be selectively sped up by choice of catalysts, such that a preferred product will be produced ahead of others at a greater level than its ultimate equilibrium fraction.
- Products can be separated out using differences in solid / liquid / gas phase change temperatures or using membranes or other reactions.

Over the years a range of particular conversions have been perfected and established as major commercial processes. Others have been developed to pilot scale, others are simply investigated in laboratories.

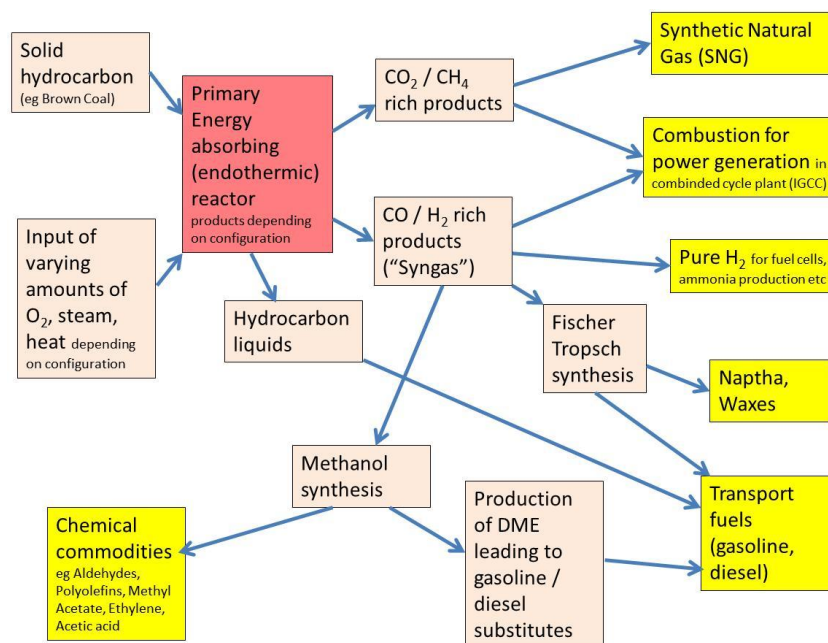


Figure 2: Possible conversion routes from Brown Coal to higher value commodities.

The possibilities for converting Brown Coal chemically for alternative uses can be illustrated as shown in Figure 2.

The heart of the processing possibilities is the primary reactor, it can be configured to produce gaseous products (usually) or produce liquids directly. In established practice the extra energy needed for the endothermic reaction is provided by providing a stream of oxygen that allows a proportion of the feedstock to be oxidised and produce the heat needed for the endothermic process. In the context of considering combinations with concentrated solar energy, it is this heating that is the obvious candidate for solar heat. The energy input needed is not just the amount needed for the endothermic reaction, but must also cover energy losses that are encountered. These occur because:

- Product gas streams exit at high temperature and attempts to re-capture the sensible heat from cooling and recycle it are imperfect.
- High temperature reactor vessels loose heat to the environment
- A range of circulation pumps and equipment must be powered.

Consequently conversion efficiencies can be around 50% or lower.

### 3.1. Products

A range of possible final product outcomes are identified as the yellow blocks in Figure 2. Their nature, market development and relative value have had a lot of influence on the development of industrial processes.

Producing methane would allow a Brown Coal feed stock to tap into existing pipeline networks for transport and distribution of a product with a high volume market and known value. This would include the potential for LNG production for export.

If gaseous products of any kind are produced, they can be combusted for power generation in a combined cycle power plant. Combined cycle plants offer the highest conversion efficiencies for existing commercially standard thermally driven power generation. In the context of coal gasification this is the integrated gasification combined cycle (IGCC) approach which offers higher efficiency and lower GHG power production than conventional steam cycle brown coal power stations.

A gasification reactor tailored for maximum H<sub>2</sub> production can be followed by standard CO<sub>2</sub> separation processes to give a pure H<sub>2</sub> stream. H<sub>2</sub> has an existing market and value as a feedstock for other chemical processes including ammonia production (one of the biggest global commercial processes). Fuel cells that convert it to electricity at very high efficiency are at an early stage of commercialisation. Depending on future developments, pure hydrogen may or may not become a major vector for energy for transport, storage and export. It has the main disadvantage that it is difficult and costly to store large amounts of it.

Syngas mixtures of H<sub>2</sub> and CO are the feedstock for Fischer Tropsch conversion. The process has a long history dating back to pre-war Germany and was developed precisely for the purpose



of converting coal to liquid transport fuels. South Africa became a dominant player following many years of economic blockade. Product streams vary with configuration and subsequent refining is needed to deliver a range of liquid fuels that meet existing fuel standards (gasoline, diesel, aviation fuel etc).

Syngas is also the feedstock for methanol production. Methanol synthesis is another of the world's biggest commercial chemical processes. Methanol is a basic building block for a range of chemical products. It can in principle be used directly as a transport fuel (racing cars sometimes use it). Processing via Di Methyl Ether (DME) can transform it directly to gasoline or diesel compatible fuel.

Direct liquids production in the primary reactor also leads to a product stream needing subsequent refining. Conceptually it can be imagined as equivalent to combining a gasification and Fischer Tropsch reactor into one integrated process / unit.

### 3.2. Primary Reactors

Gasification reactors can be built in a range of different configurations, coal gasification or biomass gasification produce slightly divergent approaches however the fundamentals are the same.

Reactors can be fixed bed, entrained flow or fluidised bed according to how the solid material is dealt with. Figure 3 illustrates the conceptual differences. Fixed bed reactors involve vessels packed with macro sized lumps of coal through which the gas phase reactants and products move. The bed of solid can be continuously replenished using screw feeders or other mechanisms, to make up for material that is consumed and ends up as ash. In entrained flow reactors, finely ground solid material moves together with the gas phases through progressive zones in a reactor. Fluidised beds go a step beyond this and use extra inert solid material together with enhanced circulating gas flow, to produce a situation of rapid circulation of the solid particles. Sometimes the extra solid phase contains catalyst particles to enhance the rate of particular reaction steps. This results in very good heat transfer and homogenisation of the reaction conditions through out the reactor.

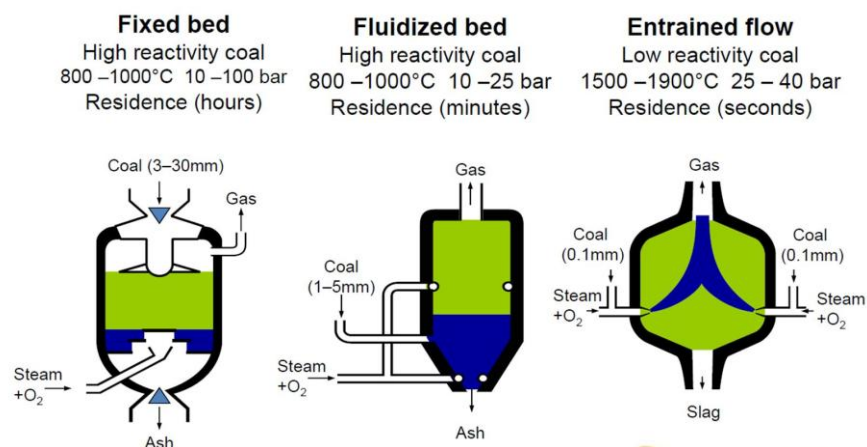


Figure 3: Conceptual illustration of gasification approaches reproduced from Woskoboenko (2012).

Fixed bed gasifiers can be further categorised as counter current / updraft, co current down / draft or cross draft according to the direction of gas flow in relating to the bed of solids that is assumed to be fed from the top and exit as ash at the bottom of a reactor vessel. For modern coal gasification, high temperature entrained flow designs dominate. Nikolaos et al (2012), Moore (2012), Barnes (2011).

There are a sequence of processes that the solid material goes through before it is fully consumed, usually these correspond to zones within the reactor. Four zones can be identified starting from the point of solid material entry;

- Drying zone where material is heated to around 200°C and moisture is driven out
- Pyrolysis zone, temperature increases to around 500°C, tar, oil and char are formed
- Reduction zone, temperatures between 500 – 800°C, hot gases (H<sub>2</sub>O and CO<sub>2</sub>) from combustion react with char and are reduced.
- Combustion zone: char is oxidised with air or oxygen which produces the heat to sustain all the endothermic processes.

An innovative new approach is supercritical water gasification (SCWG). The critical point for water is 22MPa, 374°C, above this pressure one cannot distinguish a phase change as water is heated. Water has changed chemical properties at these conditions and is essentially a very good solvent for hydrocarbons (see for example Cheng and Zhang (2004), Jin and Zhang (2011), Li et al (2010), Yamaguchia et al (2009)).

SCWG has not yet been applied commercially. Batch reactors have been used for research purposes. A continuous flow reactor seems preferred. For this the preferred approach is to inject the coal and water together as a slurry. Use of a slurry that can be pumped by a high pressure pump is one of the few practical methods of continuously introducing solid material to a very high pressure reactor.

If temperatures are kept below 400°C, methane formation can be favoured. However long residence times and catalysts are needed. This could have advantages if synthetic natural gas (SNG) were the desired product. It could also allow linear concentrators to drive operation (see section 4).

At supercritical conditions, above 600°C very high fractions of hydrogen production result.

Catalysts can be employed to selectively enhance hydrogen production for example. If syngas (mixtures of CO and H<sub>2</sub>) for feed to Fischer Tropsch is desired then conditions and catalysts can be tailored to encourage the reverse water gas shift reaction and so suppress CO<sub>2</sub> production.

Hydrocarbons with high water content are particularly suited to SCWG since the need to dry the material and high energy consumption doing so is no longer necessary.

A challenge however, is that slurries may require an excess of water and this results in a larger amount of sensible heat in an exit product gas stream

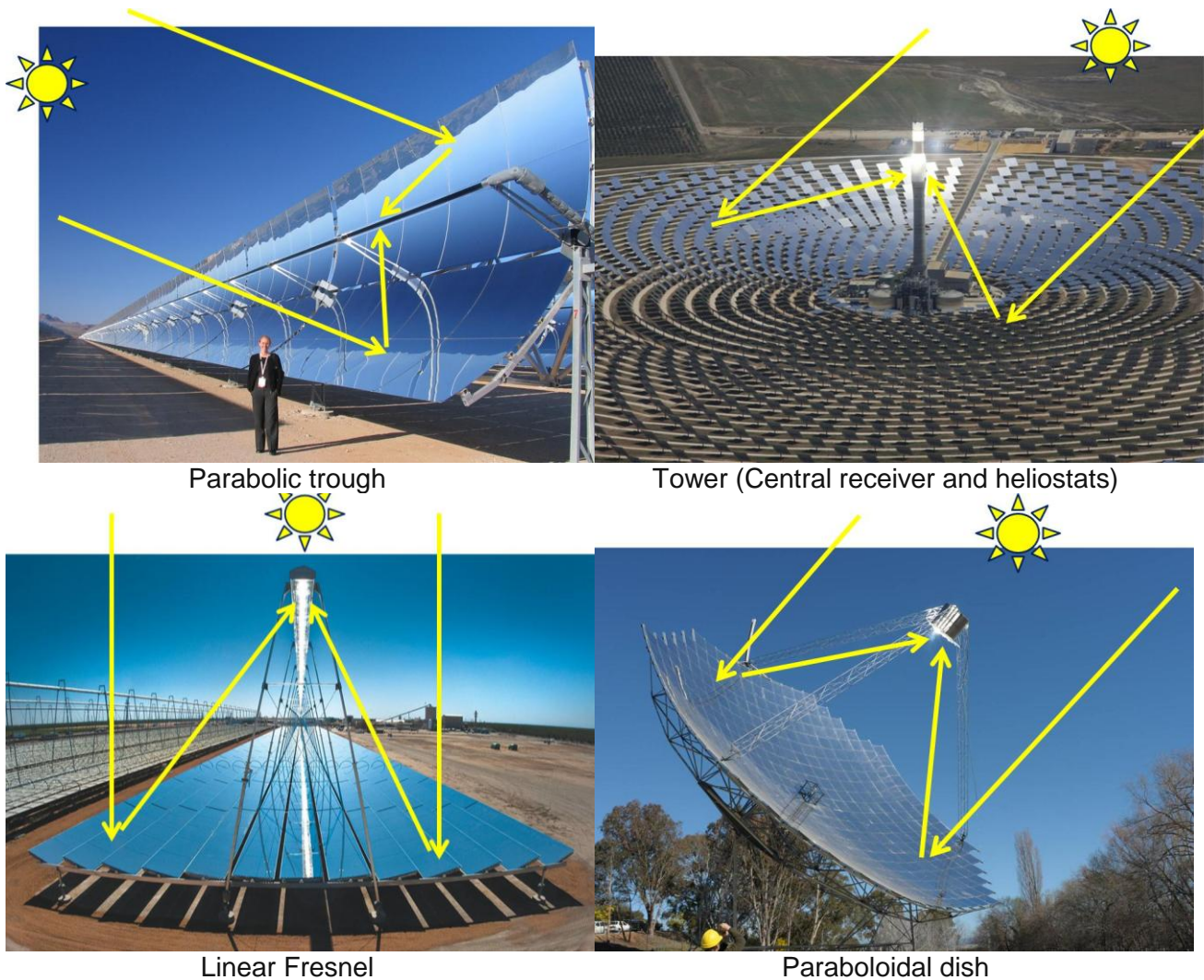
More detail on the chemical reactions and processes encountered is presented in Appendix D.





## 4. STATUS OF SOLAR CONCENTRATING TECHNOLOGY

### 4.1. Solar Concentrator Technologies



**Figure 4: The four commercially applied approaches to solar thermal concentration.**

Concentrating Solar Thermal technologies use arrangements of mirrors to focus Direct Beam solar radiation to receivers where high temperatures can be produced as illustrated in Figure 4. Systems can be categorised as:

- Parabolic trough systems that focus the sunlight to linear receivers using mirrored troughs that track the sun East to West.
- Tower/ Heliostat systems that use a field of 2 axis tracking almost flat mirrored heliostats that all move independently and focus the sun to a fixed receiver on top of a tower.

- Linear Fresnel systems that are a linear analogy of the Tower / Heliostat system, with a series of rows of long mirror strips working independently to focus radiation to a fixed linear focus.
- Parabolic dishes that use dish shaped mirrors tracking in two axes to always point directly at the sun and focus the radiation to a receiver at a single point.

Activities in the early 1980's produced 9 trough based power stations in the Mojave desert in California with capacities up to 80MW<sub>e</sub> and a combined installed capacity of 354MW. These continue to operate on a commercial basis and with a 20 year track record, have established the trough as the lowest technical risk system.

The original Californian plants plus all commercial power plants built since then employ steam turbine based power generation. As such CST basically builds upon conventional power generation technology that is responsible for 90+% of the world's electricity.

The potential to build in thermal energy storage (TES) as an inherent part of a CST system with minimal impact on cost and efficiency and the advantages of dispatchability has long been recognised. With dramatic reductions in the cost of Photovoltaic systems, the inherent TES capability of CST is currently recognised as its major competitive advantage.

CST activity had a 15 year hiatus but restarted in 2006, following policy initiatives in Spain and South West USA states. At the end of 2012, installed CST capacity has increased to close to 2GW. The first plants are now being constructed in Nth Africa and the Middle East and this is partly linked to ideas of providing solar electricity to Europe via undersea HVDC links. India has commenced construction of its first projects under a national target of 20GW of solar by 2022.

Compound annual growth rates have averaged 19%/year if calculated from the mid 1980's but have averaged 40%/year over the last 6 years. Forward growth rates seem highly likely to fall somewhere between 20%/yr and 40%/yr.

With the bulk of construction being the mature trough technology, there is increasing competition from companies offering collector fields or components for these. More than 6 major companies are offering large trough systems, all with 5m apertures. Some of these companies are introducing new wider aperture trough products to reduce cost. There are two established companies providing the evacuated tube receivers (Schott and Siemens) and several new entrants on the horizon (particularly from China). There are several companies providing the mirror facets.

Tower systems are the next most mature, with three new multi-megawatt commercial systems now in operation and a range of demonstration systems operating or under construction. Tower systems operate at higher temperatures and offer higher conversion efficiencies. A range of more innovative approaches to energy capture are investigated. There are 6 major companies offering commercial systems.

Linear Fresnel is at a slightly earlier stage of commercial deployment. Three companies have constructed modest scale working demonstrations of linear and the first serious commercial



system (Novatec's PE2 30MW plant in Spain) came on line at the end of 2012, more are under construction. In Australia, the first serious commercial CST system, is the Kogan Creek Solar Boost project, that will add 40MW<sub>e</sub> equivalent via an add on of Fresnel collectors to Kogan Creek power station in Queensland, which is on track for completion mid 2013.

Dishes are the least mature approach, activity is largely confined to demonstration systems of dishes with small focus mounted Stirling engines. They do offer the highest optical efficiencies and concentration ratios of all the options. Table 2 summarises the various features and status of the approaches.

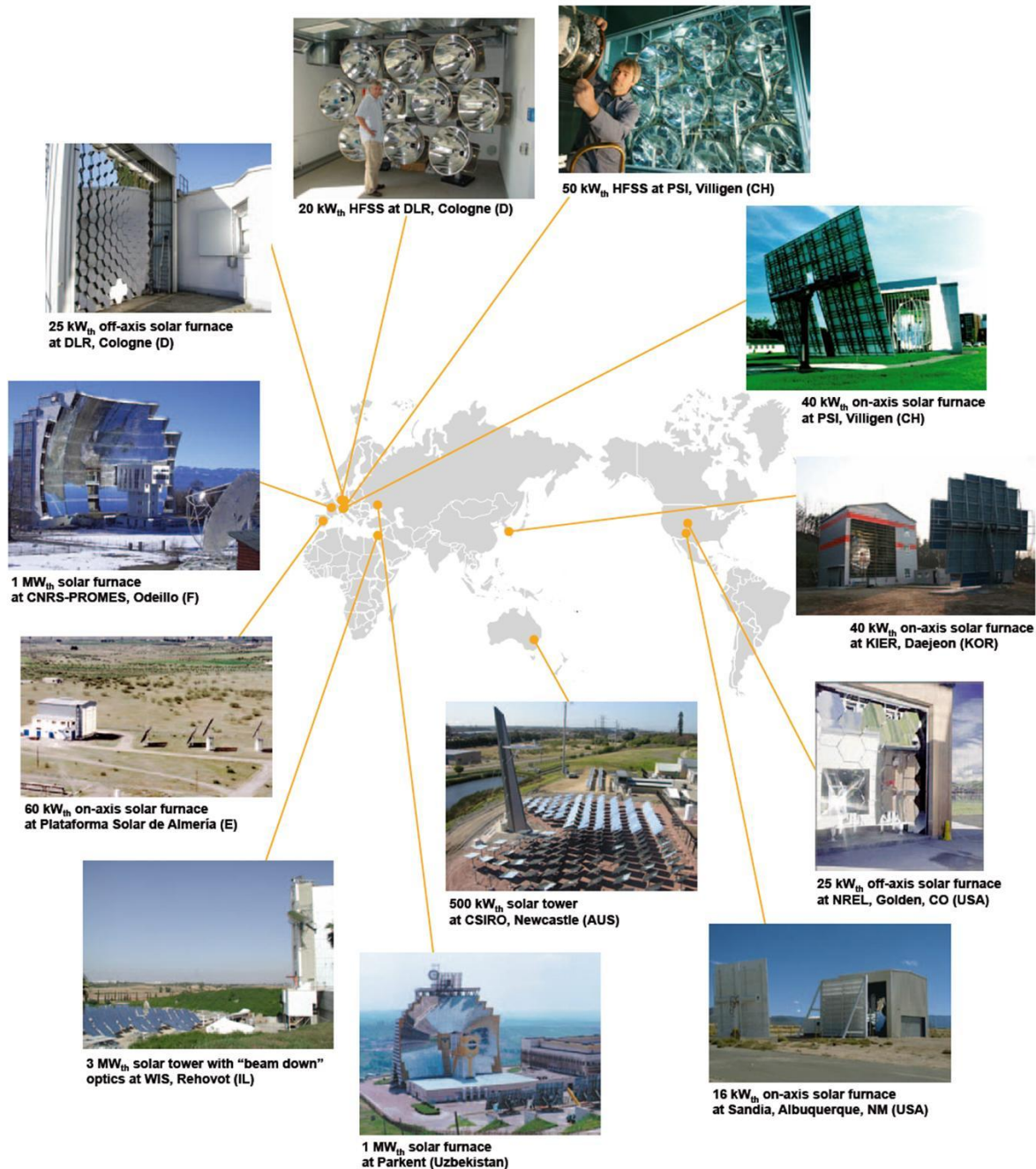
**Table 2: Summary of CSP technology characteristics and status.**

Technology	Focus type	Typical focal region average radiation flux	Practical Operating Temperature for thermal conversion	Commercial maturity	Installed Generating Capacity as at mid 2012
Parabolic Trough	Linear	50 -100 kW/m <sup>2</sup>	150 to 500°C	High	1,800 MW <sub>e</sub> (approx. 5,500 MW <sub>th</sub> )
Central Receiver Tower	Point	300 – 1500 kW/ m <sup>2</sup>	400 to 1,500°C	Medium	60 MW <sub>e</sub> (approx. 180 MW <sub>th</sub> )
Linear Fresnel	Linear	50 – 100 kW m <sup>2</sup>	150 to 500°C	Medium	38 MW <sub>e</sub> (approx. 120 MW <sub>th</sub> )
Parabolic Dish	Point	500 – 2000 kW/ m <sup>2</sup>	400 to 1,500°C	Low	1 MW <sub>e</sub> (approx. 3 MW <sub>th</sub> )

For solar fuels processes, a particular variation of the tower heliostat system, involves installing a hyperbolic convex mirror system near the focus on the tower, such that the focal point is re-directed to ground level. This is referred to as the “Beam Down” approach.

For solar fuels R&D, a configuration called a solar furnace is often used. This typically combines an array of heliostats adjusted to direct a horizontal beam of radiation to a parabolic dish that is fixed in a vertical orientation. The result is a stationary focal spot. The dish and focal region are usually installed in a laboratory building fitted with shutters. The combination of laboratory environment and stationary focal region is ideal for complex solar chemistry experiments. It is not however suggested as a likely configuration for a large commercial system due to the complexity and expense of construction. Another approach employed for R&D purposes is a solar simulator employing high intensity lamps focused to a simulated solar focal region.

Figure 5 illustrates some of the key R&D facilities around the world which are also those that are the location of much of the Solar Chemistry R&D activity.



**Figure 5: Key solar concentration R&D facilities around the world, reproduced from Meir and Sattler (2009).**

A recent in depth study of concentrating solar for power production has been prepared for the Australian Solar Institute by ITPower, (Lovegrove et al 2012). This reference is a good source of further information. Amongst other things, it has reported a careful analysis of capital costs in an Australian context, used these to determine Levelised Cost of Energy and looked at the expected cost reduction trajectory.



It was concluded that for the stage of the industry, there was insufficient information to distinguish between the technology approaches on cost of energy developed. A set of technology neutral cost estimation factors was established for the various components of a system, such that systems with varying amounts of thermal storage could be compared, as reproduced in Table 3.

**Table 3: Estimated costs for a notional large capacity CST system in Australia (AUD 2012).**

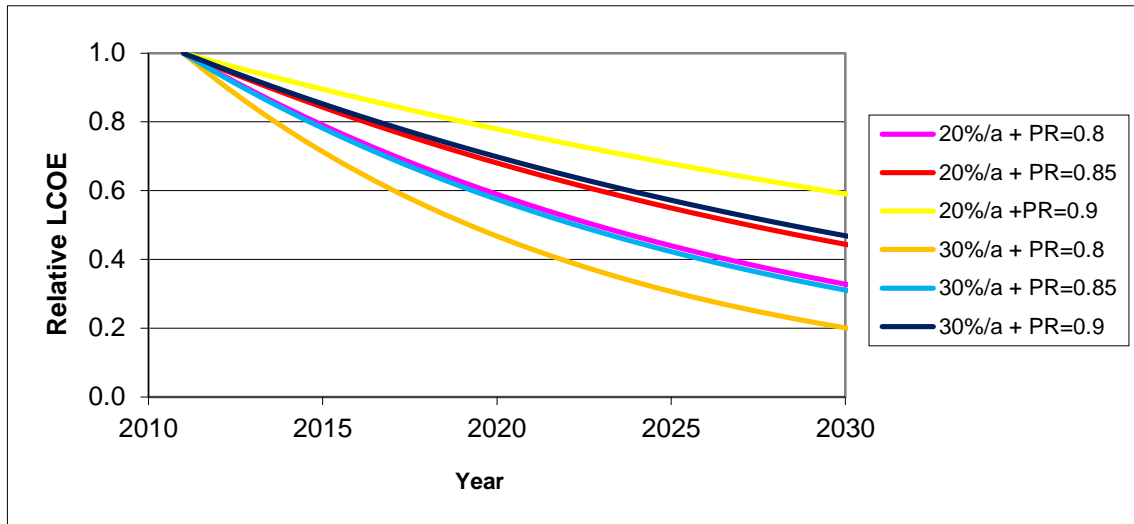
Subsystem	Per unit cost	Note / unit
Concentrator field (excluding receivers and HTF)	402	\$/kWth capacity, delivered to power island at design point
Receiver/ transfer system (including receivers, HTF, piping, Tower as appropriate)	246	\$/kWth capacity, delivered to power island at design point
Thermal Storage System	80	\$/kWhth of installed thermal energy storage capacity
Steam turbine Power block	882	\$/kWe output capacity
BOP and Other	529	\$/kWe output capacity
Indirect project costs	25%	Of subtotal of others (=20% of total)

It is these numbers that have been used to deduce the cost of energy numbers for CST systems that are included in the bottom three rows of Table 1<sup>2</sup>. In the context of a combined solar thermal brown coal system, it is the concentrator field and the receiver system that is of most interest. Storage may be contemplated if the solar system was simply providing process heat and it was judged worthwhile to attempt to do this on a 24 hour basis. The Power Block could well form part of an integrated system design optimised for multiple income streams.

Analysis of previous studies and historical data, suggests that the industry is likely to grow global deployment at between 20%/year and 40%/year from 2012 onward. Based on standard learning curve models for cost reductions with deployment due to manufacturing and performance improvements, a progress ratio applied per doubling of installed capacity of between 0.8 and 0.9 was suggested. On this basis costs would reduce in relative terms on a trajectory somewhere between the bounds shown in Figure 6.

In reality each subsystem and also O&M costs could experience different cost reduction trajectories. However in the absence of detailed data, it was assumed that all capital costs and O&M and hence LCOE all experience the same relative cost reduction trajectory.

<sup>2</sup> Financial assumptions used were; 25 year life, 60% debt, 7.8%/yr loan interest (nominal) over 15 years, 10.3%/year nominal discount rate for equity, 2.5%/yr inflation and no tax.



**Figure 6: Relative cost reduction projections for CST from Lovegrove et al (2012). To a first approximation, these can be applied to either cost of energy or capital cost and applied equally to subsystem contributions.**

## 4.1. Solar Chemistry

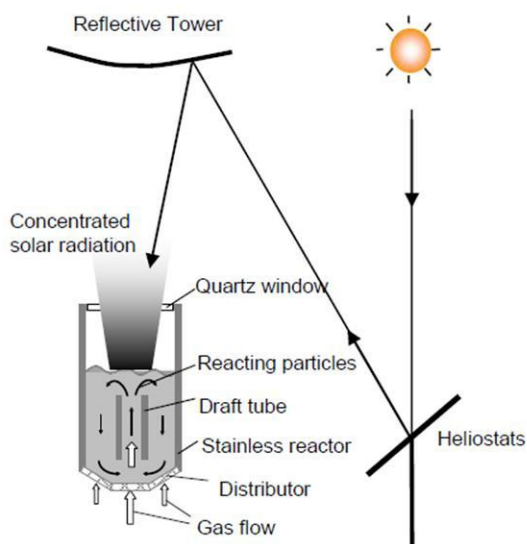
Investigation of Solar Fuels is a core area of interest under the IEA program “Solar Power and Chemical Energy Systems” (SolarPACES, [www.SolarPACES.org](http://www.SolarPACES.org)). The Solar PACES program has published an overview report on Solar Fuels (Meier and Sattler 2009). Much of the activity is associated with long term developments aimed at production of hydrogen by multistep water splitting. Possibilities for producing hydrogen by the decarbonisation of fossil fuels are also reviewed. For solar driven operation, oxidation of a fraction of the hydrocarbon is no longer needed to drive endothermic processes. Three approaches are considered, characterised as; cracking, reforming and gasification.

- Cracking refers to the direct thermal decomposition of material in the absence of other reactants. It requires very high temperatures and preserves the C H ratio of the original material.
- Steam or CO<sub>2</sub> reforming is dominantly applied to methane (natural gas) but could be applied to other gaseous / fluid feedstocks to decompose them to high hydrogen content mixtures. It is a catalytic process requiring external input of heat.
- Solar steam gasification has been tested with coals and oil shales. In this regard all the processes encountered in non-solar gasification can be encountered, with external heat input substituting for the need to feed oxygen to the process.

An active group at the university of Nigata (Japan) have explored solar gasification of coal coke particles (Gokon et al 2012, Liuyun et al 2012, Gokon et al 2011, Kodama et al 2002).



Their reactor concept is a windowed volumetric unit configured such that radiation shines down vertically. This is a simulation of a situation that would represent a beam down optics configuration with a tower / heliostat plant as shown in Figure 7. The beam down configuration is favoured by many solar chemistry researchers as it makes a easy to design and operate reactor configuration. For their lab scale experiments, a 3 kW reactor irradiated with a solar simulator based on high power Xe lamps is used.



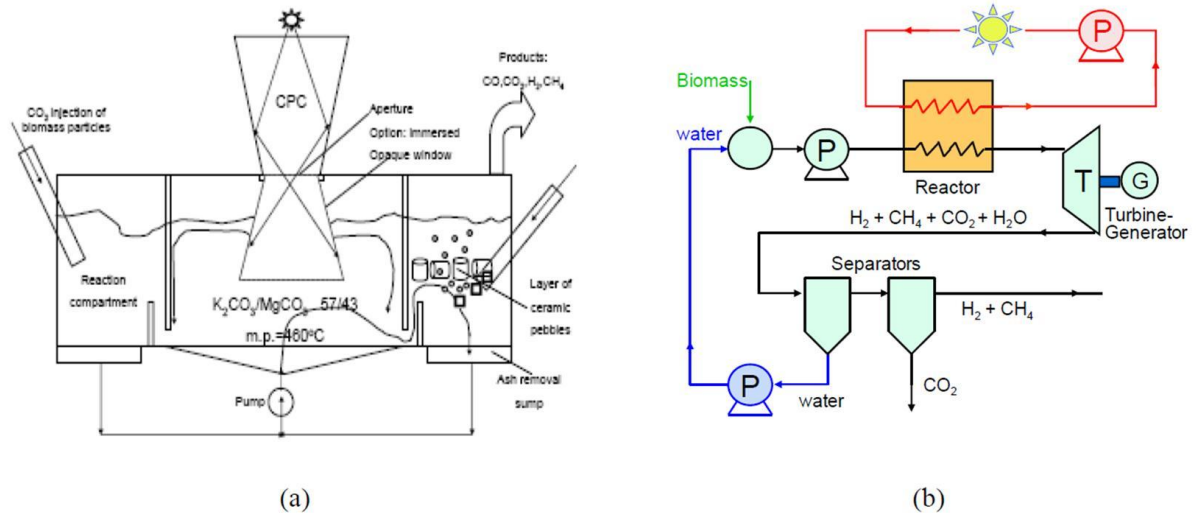
**Figure 7: Windowed receiver reactor with internally circulating fluidised bed combined with beam down solar concentrating system, reproduced from (Gokon et al 2011).**

Both steam gasification of coke and  $\text{CO}_2$  gasification are targeted. Together the two reactions allow tailored ratios of  $\text{CO}$  and  $\text{H}_2$  to be produced. Methanol and DME synthesis is suggested as a route to allow energy transport from sunbelt countries like Australia to Japan.

Radiation to chemical energy storage efficiencies could be 30-40% but values around 10% have been reported from early experiments. Operation around  $1000^\circ\text{C}$  is targeted and their experiments show conversions of coke up to 73%.

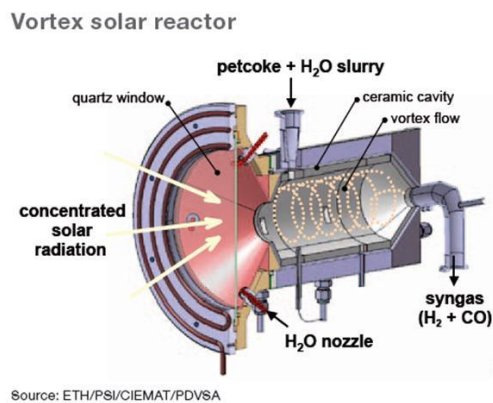
The Weizmann Institute in Israel has also played a lead role in solar gasification work (eg Zvegilsky et al (2012), Ganini et al (2011) ). They have examined Solar Pyrolysis and gasification of rice husks. They have tested both SCWG and an approach whereby the material is dispersed in molten salt.. Husks are notable for containing high levels of silica, up to 22% by weight can be inorganic matter. The approach could be easily transferred to Brown Coal.

Both methods are shown to achieve high conversion of the biomass to gas mixtures of  $\text{H}_2$   $\text{CO}$   $\text{CH}_4$  and  $\text{CO}_2$ .



**Figure 8: Concepts from Zvegilsky et al (2012), for a) gasification of rice husks in a solar heated molten salt medium and b) Solar driven supercritical water gasification.**

They propose receiver / reactor scenarios for both approaches as illustrated in Figure 8. For the molten salt approach, a ground mounted tank of salt would be continuously heated by a tower system with beam down optics and operated at around 900°C. Biomass would be fed in and product gases collected. It is implied that ash is insoluble in the salt and could be collected from the bottom of the tank. The SCWG route proposed is to be at relatively low temperature, 450°C – 550°C . This would allow use of a linear concentrator (eg troughs) and a separate heat transfer fluid (HTF) transferring heat to the reactor is suggested. A key part of the proposed SCWG proposal is that the reactor products, which would contain a large amount of excess steam, would be initially expanded through a turbine generator. It is also suggested that if the hydrogen were subsequently converted in a fuel cell, the combined solar to electric conversion efficiency could reach 50%.



**Figure 9: Vortex solar reactor for pet coke gasification as applied in the SYNPET project reproduced from Meyer and Sattler (2009)**

The biggest effort to date that is directly applicable to coal gasification is the SYNPET project, a joint project involving Petroleos de Venezuela (PVDSA), the Spanish research organisation

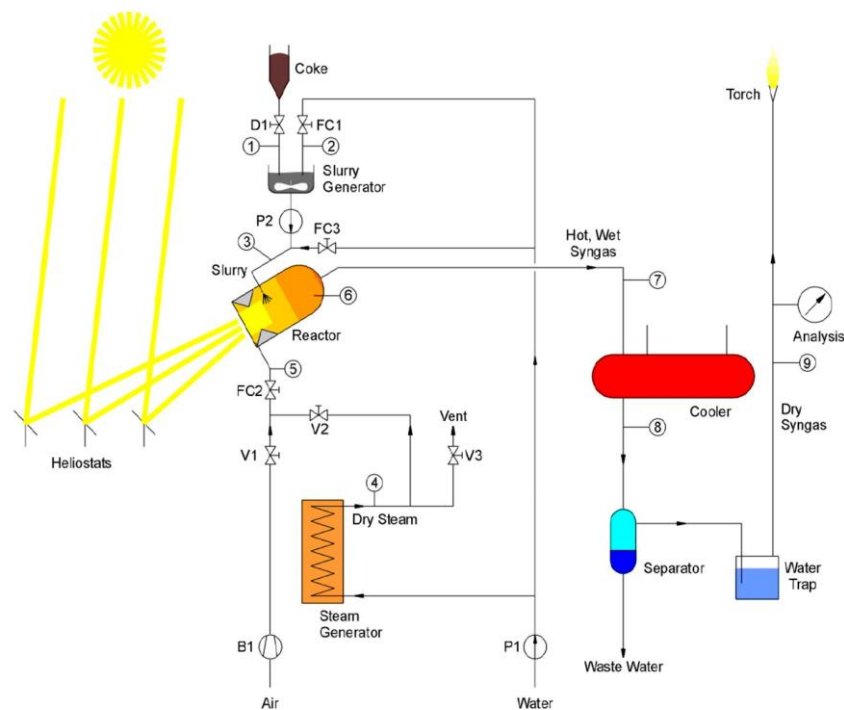




CIEMAT and the ETH in Switzerland (see Vidal and Denk (2011), Z'Graggen et al (2006), Z'Graggen et al (2007), Z'Graggen et al (2008), Z,Graggen and Steinfeld (2008)). The reactor concept is shown in Figure 9.

Preliminary experimentation was carried out at the Paul Scherrer Institute's solar furnace in Switzerland at power level of 5 kW. Two approaches were tested; one where petcoke particles and steam were injected separately and the other where petcoke particles and water were injected together as a liquid slurry. Chemical conversions of petcoke reached up to 90% and 85%, respectively.

This was followed by a test campaign on the 500kW system using the CESA 1 tower system at PSA in Spain, preliminary results showed 60% thermal receiver efficiency.



**Figure 10: Arrangement for solar gasification with 500kWth reactor at the Plataforma Solar Almeria CSA1 solar tower under the SYNPET project (Vidal and Denk 2011),**

There is an extremely large body of past work on gas phase solar chemistry that is less directly relevant. Steam reforming of methane using high temperature catalytic reactors of various sorts has been investigated for its role as a closed loop energy storage mechanism, a source of solar enhanced gas for Combined Cycle power generation or a solar derived syngas for liquids production. The CSIRO group in Newcastle is a strong player in this area and continues to develop their "SolarGas" process with these ends in mind (Stein et al 2009). Steam reforming of methane could be applicable as a second stage of processing following an initial coal gasification step.

The Solar Thermal Group at ANU<sup>3</sup> has worked for many years on solar decomposition of ammonia using packed bed catalytic receiver reactors (Dunn et al 2012). This has no direct relevance for coal gasification, however, their solar reactor, using Inconel tubing and designed for operation to 30MPa and 700°C (see Figure 11) has proven operation under conditions that would be encountered with High Temperature Supercritical Water Gasification.



Figure 11: ANU's ammonia cracking receiver / reactor designed for operation at up to 30MPa 700°C.

## 4.1. Advanced Solar Chemistry

As noted above, work on direct solar thermal splitting of water receives considerable attention. The attraction is that a pure solar based fuel can be produced that meshes with previous and continued hopes for a hydrogen economy.

In a similar manner it is possible to directly split CO<sub>2</sub> into carbon / CO mixtures. A combination of these two could provide the syngas feedstock for liquid hydrocarbon synthesis, essentially reversing the process of combustion. These are however very difficult processes to engineer and are categorised here as “advanced solar chemistry”.

To understand the challenge, it is necessary to realise that a reaction that absorbs energy to drive it may be more or less ‘difficult’ to drive according to the stability of the molecular bonds in the feedstock. Feed-stocks with very stable bonds require the energy to be provided at much higher

<sup>3</sup> Previously lead by the lead author of this report.

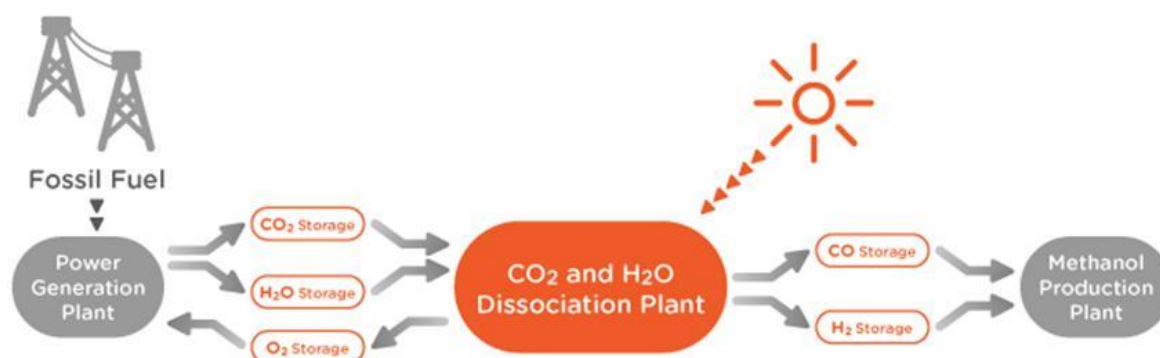


temperatures. Both water and  $\text{CO}_2$  fall in this category<sup>4</sup>. Temperatures of the order of  $3000^\circ\text{C}$  would be needed for significant simple decomposition, outside the practical limits of CST systems. This can be circumvented by achieving the result using a multiple reaction cycle that has the net result of splitting the water or  $\text{CO}_2$  or alternatively driving the reaction with a mix of heat and electricity.

The challenge with multi-step processes, is that each step must be separately engineered and they typically involve solids and / or complex separation processes. The thermal efficiency via product heat recover and receiver efficiency must also be maximised for each step.

It is also possible to imagine a closed cycle for solar energy storage that involves splitting a mixture of  $\text{CO}_2$  and water, producing syngas, synthesising a hydrocarbon for storage and transport to a point of use. The hydrocarbon would then be oxidised / combusted and the  $\text{CO}_2$  captured and returned for solar splitting. In such a closed cycle, there would be no emissions and inventory of carbon would only need to be provided once.

In the context of considering solar / coal hybrid processes, an advanced system that splits both  $\text{CO}_2$  and water could potentially be used to recycle the  $\text{CO}_2$  stream from coal combustion. In this case the initial combustion process could generate electricity and the subsequent solar splitting would then lead to production of fuels for transport to and end user. The net effect would be to get a double use from the same final amount of  $\text{CO}_2$  emission or required  $\text{CO}_2$  sequestration requirement (Figure 12).



**Figure 12: Advanced solar chemical processing of fossil fuel reproduced from (<http://newco2fuels.co.il/Solutions.aspx> ).**

One of the approaches is championed by “NewCO<sub>2</sub>fuels” a start-up company out of Israel<sup>5</sup>, that is represented in Australia by Greenerth energy. The process they are developing is understood to be based on a hybrid direct electrical plus thermal, integrated receiver. There appears to be little published on the detail of the process. The key proponent / originator is Prof Jacob Karni, who has been a lead figure in solar chemistry work at Israel’s Weizmann Institute for many years.

Stamatiou et al (2010) discusses the possibility of producing syngas mixtures from water and  $\text{CO}_2$  feedstock via thermal cycles involving zinc or ferrites redox reactions. Two step thermo-chemical

<sup>4</sup> In chemical terms the Gibbs free energy of reaction compared to the Enthalpy of the reaction quantifies this. It is also a quantification of the relative amount of ‘equivalent work’ or ‘Exergy’ needed to drive the reaction.

<sup>5</sup> <http://newco2fuels.co.il/Solutions.aspx>

processes are suggested, with a high temperature reduction of an oxide achieved with solar energy, followed by an exothermic process in which the reduced material is re-oxidised by the water / CO<sub>2</sub> mixture, also at elevated temperatures, with consequent production of syngas mixtures.



## 5. SCENARIOS FOR COMBINING SOLAR AND BROWN COAL

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### 5.1. Process steam / heat

The lowest technical risk approach to combining CST inputs with coal conversion processes would be to use proven approaches to coal conversion and identify points where process heat could be added. Proven CST approaches for providing that heat can be listed as:

- Heat transfer oil heated by linear concentrators to up to 400°C.
- Molten salt heated by linear concentrators up to 450°C.
- Molten salt heated by tower systems up to 600°C.
- Steam heated by tower or dish systems to 650°C.
- Steam heated by trough or linear Fresnel systems to 500°C.

Process heat could be added to the reactant stream preheat prior to entering reactor systems via heat exchangers. Alternatively heat exchange mechanisms (such as internal tubing) could be added to standard endothermic reactor designs to provide heat input via the solar heated heat transfer fluid.

The challenge with this approach is that the solar contribution becomes a means of reducing the amount of coal that would otherwise be oxidised to provide the same heat. Given the low cost of coal and the high investment cost for the concentrating solar systems, this would be challenging economically unless there was a very high price on CO<sub>2</sub> operating.

Use of standard solar HTFs could work well in configurations where co-generation of electricity is contemplated. The concept of the Integrated Solar Combined Cycle (ISCC) plant is now established with several commercial scale working power plants around the world. It involves a gas fired combined cycle plant with an oversized steam turbine that is able to also accept further steam from a solar field when available. An IGCC system could also be configured in this way, with the option of using solar heat both for the power cycle and to contribute to the energy consumption of gasification.

Another approach to use of solar process heat that has been mooted is for the regeneration of chemical scrubbing of CO<sub>2</sub> from flue gas. It is understood that CSIRO is currently investigating such an approach.

### 5.2. LTSCWG in linear concentrator with slurry

Low Temperature Super Critical Water gasification (LTSCWG) operates at just over the 374°C critical temperature of water and at pressures above the 22MPa critical pressure. Slurry phase operation is one of the options that has been tested and nickel catalyst is employed to give a

product has with a large fraction of  $\text{CH}_4$  and  $\text{CO}_2$ . The temperature is well within reach of linear concentrators so it is possible to contemplate tubular reactors in either trough or LFR system receivers.  $374^\circ\text{C}$  combined with 22MPa pressure is well within the capabilities of standard stainless steel materials. A question that would need to be answered is whether the corrosive nature of SCW necessitates the use of expensive high nickel alloys as it does for High Temperature Super Critical Water.

The standard approach to receivers for troughs and for some LFR systems is an evacuated tube system where a central steel tube is surrounded by a glass sheath with the intervening space evacuated to reduce heat loss. Performance is further enhanced by a coating on the steel tube that is highly absorbing of solar radiation whilst being a low emitter of thermal radiation from the hot tube surface. This configuration could be adapted to an internal tube of a material and thickness needed for LTSCWG. A question that would need to be addressed is what tube diameter would be needed and would it be practical within the receiver. This is dictated by the mass flow of reactants that would be dictated by matching the reaction rate to the solar flux level, which in turn would determine the receiver / reactor tube diameter.

Management of slurry transport through a complex network of distribution pipes to the solar field would represent an engineering challenge. Particular attention to start-up and shut down strategies would be needed. Possibly flushing with pure water might be needed. Fine slurries incorporating surfactants that do not settle even when not flowing could possibly be used.

As noted previously, LTSCWG would yield high levels of methane production. This could be treated as the end product and effectively sold into the natural gas market or used in an IGCC plant. Alternatively, a further step of steam reforming of methane in a point focus concentrator with a catalytic reactor at around  $800^\circ\text{C}$  would be needed to convert to high levels of hydrogen.

A challenge with the SCWG approach is that excess water is involved, a large amount of collected solar energy would be present in the reaction products and excess steam leaving the receivers. For viable operation it would be desirable if this fluid stream could be used directly in a turbine for power generation before separation of the gaseous products (as proposed by the Weizmann Institute group). Pre-separation of ash and catalyst solids would be necessary for this.

A positive aspect to this approach is that the receiver / reactor system would be a direct substitute for a standard receiver system at possibly similar cost. It would also replace the investment needed in a non-solar gasification reactor.

### 5.3. Direct Coal to Liquids in a linear concentrator

In the NEDO direct coal to liquids process (see Appendix D), the primary reactor involves a slurry of hydrocarbon solvent, catalyst and coal and operates at  $450^\circ\text{C}$  and 170bar. This could be operated in a similar manner to a LTSCWG system in a trough or LFR linear concentrator system. With the organic products as the liquid phase, there would presumably not be the corrosion challenges of SCWG. A range of standard pipe materials should be possible.



Similar questions around the engineering of slurry handling in the pipe networks and the diameter of reactor tubes necessary need to be addressed.

In terms of energy recovery from the product stream, it can be noted that the dominant CST power generation approach at present uses an oil based heat transfer fluid at 400°C which is then used to produce steam in boiler heat exchangers. Swapping to a hydrocarbon solvent stream at 450°C should allow power production in a virtually unchanged manner<sup>6</sup>.

## 5.4. Use of molten salt

The pioneering work by the Weizmann institute group into the use of molten salt tanks as a gasification reactor offers an attractive route. At present molten salt energy stores are used both for trough systems (peak temperature 400°C) and tower systems (peak temperature 560°C). The Weizmann proposal is contingent on a different salt type and proposes operation at 900°C. This is a challenging temperature for a tubular metal receiver but not impossible given that pressures would be low. The high temperature is presumably the motivation for proposing the use of beam down optics so that no circulation through pipe networks is needed for the high temperature salt.

A major advantage of the idea is that the system simultaneously provides a preferred approach for solar energy storage whilst itself acting as the gasification reactor.

It is an approach that is however very much in the research phase and would take considerable effort to translate to a fully engineered solution. Although it is suggested that ash material would settle out as a solid, a key questions would need to be answered around the possible changes in chemical composition and properties of the salt over time due to the accumulation of impurities from the hydrocarbon material.

The concept is actually very similar to the “HydroMax” and “Zegen” Molten metal based approaches to gasification mentioned in Appendix D.

## 5.5. HTSCWG in tower or dish

High Temperature SCWG could work with essentially the same slurry feedstock as LT SCWG. Operating temperatures around 700°C would require a point focus concentrator, either tower or dish. Reactor tubing would definitely require expensive high nickel content alloy tubes. This is however technically feasible. The Solar Thermal Group at ANU have demonstrated a prototype ammonia cracking reactor that operates on a dish and works at temperature up to 700°C and 30MPa. It is designed around an array of Inconel reactor tubes connected to manifolds for parallel flow. For ammonia cracking the tubes are packed with catalyst, for HTSCWG, a direct slurry feed to empty tubes, would be needed.

HTSCWG has the advantage of high hydrogen fractions in the product gas and so better suits production of feedstock for Fischer Tropsch reactors or as a source of hydrogen for other uses. An interesting possibility is that the CO<sub>2</sub> component remains dissolved in the liquid water as long as the pressure is maintained, whilst the hydrogen component would separate as a gas at lower

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<sup>6</sup> The extra 50°C actually has the potential to significantly improve the efficiency of generation.

temperature, thus the system could lend itself to delivering CO<sub>2</sub> capture in an integrated manner. As with LTSCWG, heat recovery approaches would be critical. Possibly the entire product stream could be used as the working fluid for power generation.

## 5.6. Gasification in a tower

Established approaches to Steam gasification could be applied on tower systems and are the focus of the majority of experimental solar gasification work to date. With temperatures up to 800°C needed the trend has been to have radiation input through windows to the reactants to avoid even higher temperatures in metal reactor walls. The vortex reactor fed with an entrained stream of coal in steam is one option. Another is the beam down approach to a fluidised bed containing coal as tested by the Nigata University group.

Once again, heat recovery from the product stream is very important. This is made more challenging by it being a lower pressure gas. Heat transfer coefficients for heat exchange are not that high so large heat exchangers would be needed.





## 6. ECONOMICS

The starting point for a consideration of the relative economic performance of solar conversion of brown coal, is an understanding of the cost structure behind non solar approaches to conversion. Many references suggest production costs from coal to liquids, gas to liquids and biomass to liquids approaches, usually without clear articulation of the assumptions behind the analysis. Other references offer capital cost estimates of plants per installed capacity.

Table 4 compares data from an initial survey of a range of references. For this indicative analysis, all costs have been escalated to 2012 values at a rate of 2.5%/year. To compare capital cost numbers to direct quoted production costs, an indicative annualisation factor of 15%/ year real has been used. To incorporate fuel costs, a 50% energy conversion efficiency has been assumed. Overall these assumptions give reasonable agreement between capital costs and production costs.

**Table 4: Estimated costs for conversion of coal to liquids**

Reference	Year of estimate	Capital cost \$/bbl/day 2012	Capital cost amortised \$/bbl	Value of coal \$/bbl	2012 cost \$/bbl
ABARE (2010) low	2000				81
ABARE (2010) high	2000				151
Takehita (2008) high	2008	76059	31.26	4.3	40
Takehita (2008) low	2008	54935	22.58	4.3	31
World Coal Institute WCI(2006) quotes DOE	2005	59434	24.43	4.3	33
WCI quotes DOE	2005	83208	34.20	4.3	43
WCI quotes DOE	2005			4.3	42
Bajura (2005)	2005			4.3	36
American Association for Advancement of Science www.aaas.org (2012)	2012	60000	24.66	4.3	33
aaas.org 2012	2012	70000	28.77	4.3	37
aaas.org 2012 low	2012			4.3	45
aaas.org 2012 high	2012			4.3	50
wikipedia	2008			4.3	39
Fagiano (2011), Altona Energy	2011	102000	41.92	4.3	51
Fagiano (2011), Altona Energy	2011				53
<b>AVERAGE</b>		<b>80,000</b>	<b>33</b>	<b>4.3</b>	<b>41</b>

It can be seen there is considerable variation in overall production cost estimates. It is notable that the numbers taken from the ABARE (2010) are considerably higher than other estimates. The reasons for this are unclear. Part of the difference could be explained by a higher energy cost for black coal if that is the assumed feedstock. There is no distinction between technology approaches in this analysis, the variation at the present time appears to be smaller than the very large uncertainty in the cost estimates.



For the purposes of this analysis an average value of \$80,000/bbl/day of installed capacity has been used corresponding to a production cost of liquids from brown coal of \$41/bbl. The uncertainty in these numbers is at least +/- 20%. It could also be anticipated that plants would be more expensive if they were;

- First of a kind in Australia
- First of a kind for a new technology variation
- Smaller than around 10,000bbl/day in capacity

Dry (2002) and other references suggest that of the capital cost, around 60% can be attributed to the primary endothermic reactor. As a first test of the economic potential of a hybrid solar / coal system it is assumed that suitable solar receiver reactor technology would actually replace the non solar primary reactor. When converted to similar energy units, the 2012 cost of a receiver system is close to the cost of a primary reactor. Reactor receivers should not fundamentally cost more than receivers for molten salt or steam generation.

Clearly concentrated solar radiation at a 2012 value of \$7.50/GJ is not going to improve on a system entirely operating on coal energy at \$0.7/GJ and would have little prospect of ever doing so. However a cost on CO<sub>2</sub> emissions, either directly via emissions pricing or indirectly via a CCS cost, would increase the effective cost of coal energy considerably. Appendix C identifies a CO<sub>2</sub> emission intensity for Victorian Brown Coal of 94kg/GJ based on the Gross Wet Specific Energy.

Based on this, Figure 13 presents the cost of liquids from brown coal as a function of carbon price for three scenarios; coal only, 50% solar energy input at 2012 estimated costs for concentrating systems and a 50% solar energy input at possible 2020 estimated costs for concentrating systems.

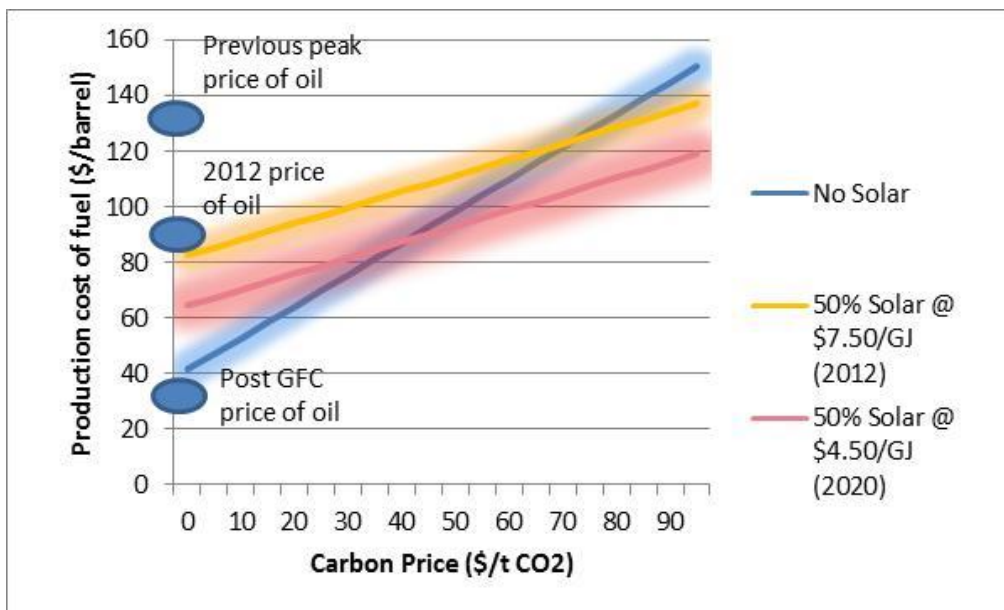


Figure 13: Comparing coal to liquids costs with and without solar input as a function of a carbon price.



These three trend lines are compared with market price for oil from the peak immediately before the Global Financial Crisis, the low immediately after the GFC and the approximate 2012 value. It would appear on this basis that ignoring cost on carbon or solar energy inputs, a brown coal to liquids plant appears to be a very good investment proposition. It is known that there are 5 or more active project proposals for plants in Australia (see Appendix D), however none have been built yet. Working against such projects, it can be observed that:

- Previous long term oil prices and the immediate post GFC price of oil would make such systems uneconomic.
- There remains a high level of uncertainty over future carbon prices and policy both in Australia and internationally and it is not out of the question that prices could increase over the life of a project sufficient to render it unprofitable.
- There will be some first of a kind cost penalties for early plants.
- The capital investment required is substantial with the order of \$1bn needed for a 10,000bbl/day system.

Considering the solar driven option, the cost of liquids produced in the absence of a price on carbon is 100% higher than coal only. It is however apparently still potentially profitable for an \$80-\$90/bbl world oil price. At present solar costs, the carbon price would need to reach around \$75/t for a solar driven system to out-perform a coal only one. At the projected lower cost of solar in 2020, this break-even point could drop to around \$40/t. The uncertainty in these numbers is very high as approximately indicated by the width of the shading. The consequence for the break even carbon price is that for 2012 numbers it could fall anywhere between \$40/t and \$100/t and for 2020, anywhere between \$10/t and \$70/t. The future of carbon pricing both in Australia and globally remains a major source of market uncertainty.

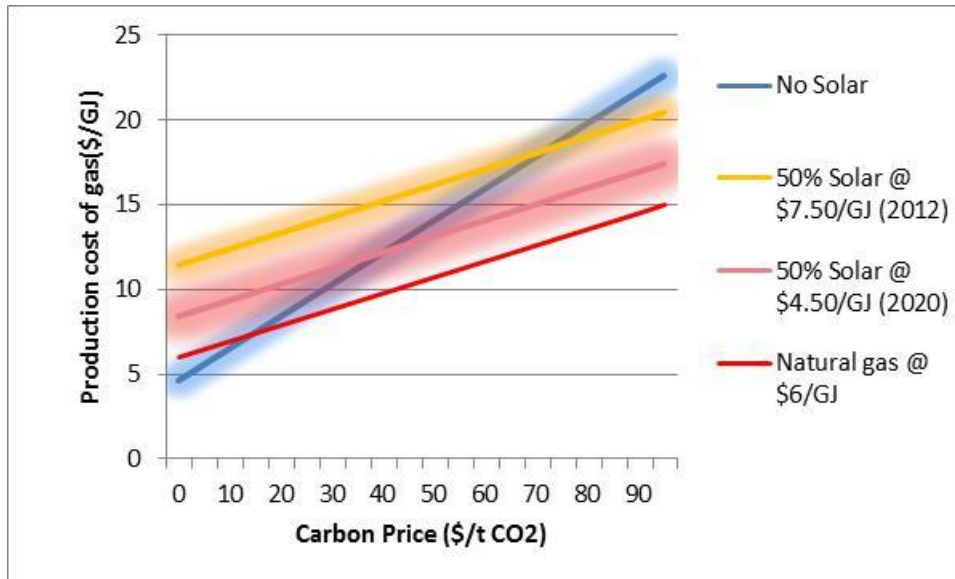
Another unknown factor is what effect carbon prices will have on international and domestic oil prices. If carbon prices simply increase oil prices in proportion to the carbon intensity, then the oil price would have a slope somewhere between the 50% solar options and the coal only option depending on the source of the oil<sup>7</sup>.

If the capital cost of the balance of plant is removed from the analysis such that it becomes an assessment of gasification only, the relativity of the values of solar and non-solar options remains unchanged and the relevant comparison is with the value of natural gas as shown in Figure 14. In this case, the non solar, zero price on carbon, value of energy is \$28.3/bbl(equivalent) ie, \$4.6/GJ, less than the current export value of LNG. Solar plus coal however comes in higher than natural gas even with 2020 cost for solar. If a carbon price is added, it appears that coal to gas conversion loses to natural gas at about \$12/t. Once again uncertainties, particularly in points of intersection, are very high. The effect of the solar component in a solar plus coal solution, is to bring the CO<sub>2</sub> intensity to equal that of natural gas and so maintain the same relativity irrespective

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<sup>7</sup> For example oil from Tar sands would have similar net carbon intensity as non-solar coal to liquids, conventional oil would be just slightly higher than solar driven coal to liquids.

of carbon price. This comparison would apply either if the gas was sold in the market place or used as fuel in an IGCC system competing with a natural gas fired CC plant.



**Figure 14: Comparing the cost of coal to gas conversion with and without solar input as function of carbon price.**

This indicative analysis has so far only looked at revenue from derived fuel sale. It is likely that a system would offer the highest Internal Rate of Return if it was optimised for multiple revenue streams. One of these would be other hydrocarbon commodities, which can not be simply investigated at this level of approximation. The other obvious source is generation of electricity.

This approximate analysis has assumed that the conversion of coal plus solar energy to liquids could be achieved at a thermal efficiency of around 50%. Much of the 50% of the lost energy would appear as high temperature exit reactant streams. If that could be converted to steam for power generation, the extra revenue would directly improve overall economic performance. To indicate the relative significance of this, if 50% of the available thermal energy were converted to electricity at a cycle efficiency of 40%, the net result would be 2 units of electrical energy per every 10 units of liquid fuel energy produced. Based on the relative values of wholesale electricity in Table 1, overall revenue would increase by around \$14 per barrel of liquid produced, with roughly half of that offset by increased capital cost of plant. If it could successfully be argued that all the electricity generation had its origin in thermal energy from the solar source and thus earn renewable energy certificates, the extra revenue would increase to around \$29/bbl less a contribution for increased capital cost. These contributions would have the effect of significantly lowering the break even carbon price between solar and non-solar options in Figure 13.



## 7. RELATIVE LOCATION OF SOLAR AND COAL

Figure 15 shows the annual average DNI incidence across Australia. Most of the continent receives more than  $22\text{MJ}/\text{m}^2/\text{day}^8$ . By international standards a value between 18 to 20 is an indicative minimum for realistic operation of a CST system. This map can be compared to the coal resources map in Figure 16.

Comparing these two maps, it is apparent that the Gippsland basin which is the source of most brown coal production at present, unfortunately coincides with some of the lowest levels of direct beam solar radiation in mainland Australia. Radiation levels are around 30% lower than levels in mid southern NSW some 500km to the north. The impact on relative output on a CST system is however even higher as a consequence of finite start up times and thermal losses that are largely fixed irrespective of input energy. The relative performance across some key locations is illustrated in Table 5

**Table 5: Relative generation of solar energy and energy cost by location.**

Site	DNI ( $\text{kWh}/\text{m}^2/\text{yr}$ )	Normalised DNI	Normalised annual generation	effective solar heat value 2012 ( $\$/\text{GJ}$ )	effective solar heat value 2020 ( $\$/\text{GJ}$ )
Longreach	2564.4	100.0%	100.0%	7.50	4.50
Moree	2254.6	87.9%	84.9%	8.84	5.30
Mildura	2124.6	82.8%	73.3%	10.24	6.14
Melbourne	1367.5	53.3%	43.1%	17.40	10.44

These results are obtained by modelling a tower system using the NREL SAM model to predict annual output. Solar data files for doing this are only available for a selection of locations. Longreach is representative of essentially the best possible sites in Australia, Melbourne is used as a proxy for Gippsland sites and Mildura is representative of the NW corner of Victoria and much of the SW of NSW. The levelised cost of energy from a CST system is inversely proportional to the annual generation level. The value of  $\$7.50/\text{GJ}$  that has been discussed corresponds to a best possible site such as Longreach, the other sites thus deliver solar input at higher cost as shown.

The Eucla and Murray basins however do coincide with high radiation levels. As do some of the key black coal producing areas. Leigh Creek in South Australia is the site of brown coal mining to support power stations near Port Augusta. It is understood to be coming towards the end of its economic life.

<sup>8</sup> In other units often used, this is  $8030\text{MJ}/\text{m}^2/\text{year}$  or  $2,231\text{kWh}/\text{m}^2/\text{yr}$ .

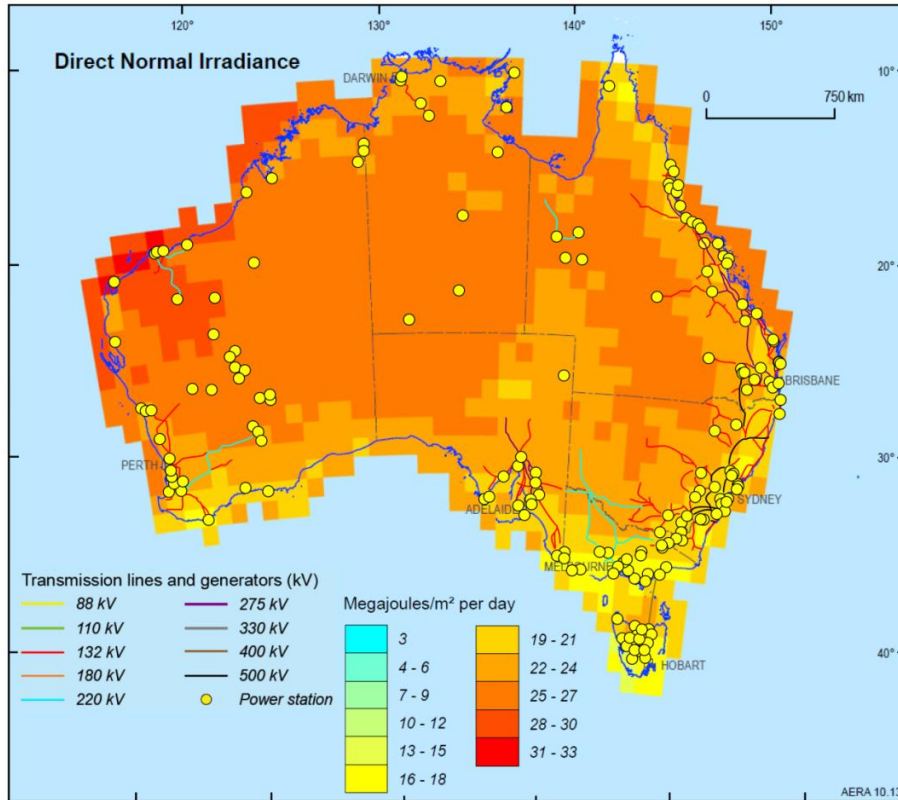


Figure 15: Average annual Direct Normal Irradiance and the transmission network (ABARE 2010)

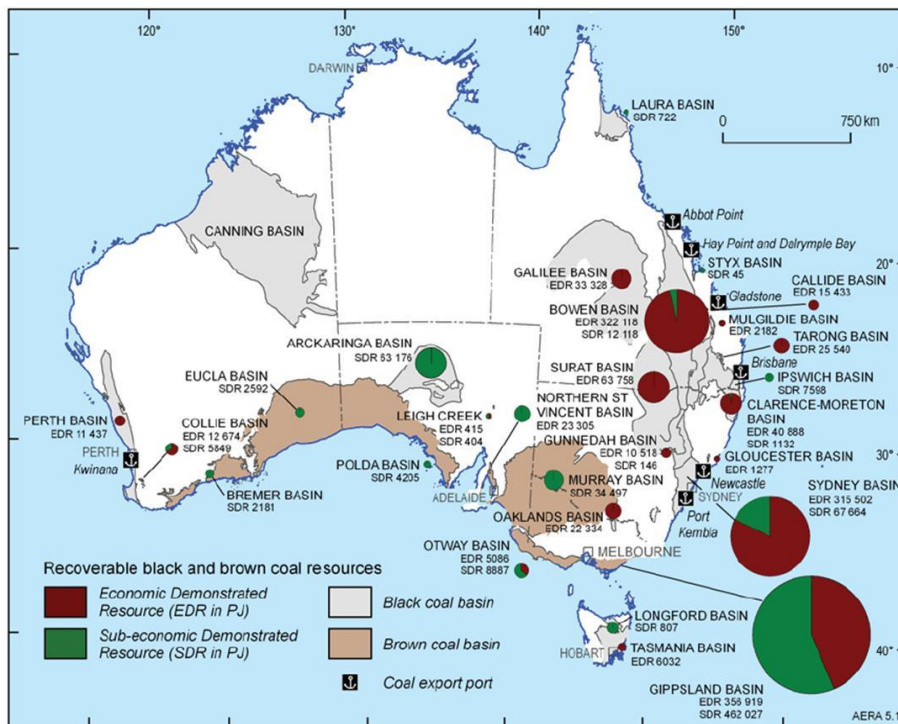


Figure 16: Coal resources in Australia, reproduced from (ABARE 2010).



Given this imperfect correlation, it is of relevance to consider the options and costs of transporting brown coal from a point a mine site to a location of higher solar resource for processing. Options for doing this include; road, rail and slurry pipeline. These have been surveyed in some detail in Appendix E. The overall conclusion is rail transport of brown coal could be achieved for an indicative cost of \$30/tkm which translates to \$0.003/GJkm at 10GJ/t. For a large scale development, a slurry pipeline is likely to deliver transport at significantly less cost than this. Using the figure of \$0.003/GJkm as indicative, it is apparent that transport of brown coal over an indicative distance of 500km would increase its input cost by \$1.50/GJ. Given the potential reduction in solar cost that can be achieved over such a distance, it would appear to be worth considering.

**Table 6: Relative generation of solar energy and energy cost by location, solar costs.**

Location		Ideal	Southern Victoria	Mildura
Value of solar heat (2020)	\$/GJ	4.5	10.4	6.1
Value of coal energy after transport	\$/GJ	0.7	0.7	2.2
Liquid value	\$/bbl	65	101	84

Table 6 compares 3 cases; the ideal case of co-location of coal with best solar, a situation representative of a Gippsland site with no transport and reduced solar resource and the hypothetical case of transport of coal 500km to gain a solar resource equivalent to Mildura. The lower estimated 2020 values of solar cost are used and it suggests that transport of coal to higher resource locations would be a better proposition than conversion in a poor solar area.

## 8. CONCLUSIONS

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Conversion of brown coal either to gaseous or liquid hydrocarbon products is a commercially proven technology. On current international prices for oil, it would appear that conversion of brown coal to liquids is an economically feasible proposition. Predicting future oil price trends is difficult however there is strong evidence to suggest it will remain high in coming decades. Conversion of coal to liquids does result in an increase in GHG emissions over conventional oil unless carbon capture and storage is also employed. The future Australian and global approach to pricing GHG emissions is very uncertain and this contributes to the investment uncertainty associated with coal to liquids projects.

On the other hand, processes that convert brown coal to gas appear to be only just cost effective when compared to gas prices and even a relatively small price on carbon would see them being uncompetitive.

Concentrating solar thermal technologies are now proven on a large utility scale, so far they have only been employed commercially to heat working fluids for power generation. However the principle of driving high temperature endothermic reactions with concentrated solar energy is well established in the R&D phase. Conversion of a hydrocarbon such as brown coal, using solar heat appears to be quite technically feasible via a number of possible routes.

Based on the uncertain cost data available, it appears that solar driven conversion of coal to liquids is just viable even with current costs of solar. Solar cost is projected to fall strongly over time so the potential return on investment should improve. A solar driven process also has the advantage of lowering the carbon dioxide emissions intensity down to a point slightly less than conventional oil. The result is that with likely 2020 solar costs, the carbon price at which it would be more cost effective than a non-solar process could fall anywhere between \$10/t and \$70/t. Choice of the solar option has the effect of significantly reducing the investment uncertainty associated with an unknown future price on CO<sub>2</sub>.

Where available brown coal resources do not coincide with good solar resources, it appears that the cost of transporting coal is sufficiently low that taking coal to a high solar site would be more cost effective than processing it in a low solar site.

Given the positive findings from this initial scoping study, a more detailed feasibility study of technical options and costs is recommended. Noting that the solar driven processes needed are still in the R&D phase, it is suggested that those aspects would be worth further investment to prove them in pilot scale.





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## 10. APPENDIX A: ENERGY CONVERSION FACTORS

The following energy conversion factors are reproduced from ABARE (2010).

Fuel	typical unit	equivalent to
Oil and condensate	1 barrel =	158.987 litres
	1 gigalitre (GL) =	6.2898 million barrels
	1 tonne (t) =	1250 litres (indigenous)/ 1160 litres (imported)
Ethanol	1 tonne =	1266 litres
Methanol	1 tonne =	1263 litres
LPG		
• average	1 tonne =	1760 – 1960 litres
• naturally occurring	1 tonne =	1866 litres
Natural gas	1 cubic metre (m <sup>3</sup> ) =	35.315 cubic feet (cf)
Liquefied natural gas	1 tonne =	2174 litres
Electricity	1 kilowatt-hour (kWh) =	3.6 megajoules (MJ)

Multiple	Scientific exp.	Term	Abbreviation
Thousand	10 <sup>3</sup>	Kilo	k
Million	10 <sup>6</sup>	Mega	M
Billion	10 <sup>9</sup>	Giga	G
Trillion	10 <sup>12</sup>	Tera	T
Quadrillion	10 <sup>15</sup>	Peta	P

Gas type	Energy content (PJ/bcf)	Energy content (MJ/m <sup>3</sup> )
<i>Natural gas</i>		
• Victoria	1.0987	38.8
• Queensland	1.1185	39.5
• Western Australia	1.1751	41.5
• South Australia, New South Wales	1.0845	38.3
• Northern Territory	1.1468	40.5
• Average	1.1000 (54 GJ/t)	38.8
<i>Ethane (average)</i>	1.6282	57.5
<i>Town gas</i>		
• synthetic natural gas	1.1043	39
• other town gas	0.7079	25
• Coke oven gas	0.5125	18.1
• Blast furnace gas	0.1133	4

Liquid fuels	PJ/mmbbl	By volume	By weight
		MJ/L	GJ/t
<i>Crude oil and condensate</i>			
• indigenous (average)	5.88	37	46.3
• imports (average)	6.15	38.7	44.9
<i>LPG</i>			
• propane	4.05	25.5	49.6
• butane	4.47	28.1	49.1
• mixture	4.09	25.7	49.6
• naturally occurring (average)	4.21	26.5	49.4
<i>Other</i>			
• Liquefied natural gas (North West Shelf)	3.97	25	54.4
<i>Naphtha</i>	4.99	31.4	48.1
<i>Ethanol</i>	3.72	23.4	29.6
<i>Methanol</i>	2.48	15.6	19.7

Solid Fuel	Energy Content (GJ/t =MJ/kg)
<b>Black coal</b>	
<i>New South Wales</i>	
Exports – metallurgical coal	29
Exports – thermal coal	27
Electricity generation	23.4
Other	23.9 – 30.0
<i>Queensland</i>	
Exports – metallurgical coal	30
Exports – thermal coal	27
Electricity generation	23.4
Other	23
<i>Western Australia</i>	
Thermal coal	19.7
<i>Tasmania</i>	
Thermal coal	22.8
<b>Lignite (Brown Coal)</b>	
<i>Victoria</i>	9.8
Briquettes	22.1
<i>South Australia</i>	15.2
<b>Uranium*</b>	
Metal (U)	560 000
Uranium Oxide (U3O8)	470 000
<b>Other</b>	
Coke	27
Wood (dry)	16.2
Bagasse	9.6



## 11. APPENDIX B: FUTURE OF OIL SUPPLY

The historical changes in oil price and future trends are the subject of much analysis and conjecture. Figure 17 illustrates the price over the period 1946 to 2012. It shows a strong increasing trend from 2004 to 2008 with a sudden reversal coinciding with the global financial crisis, with a return to close to 2008 prices in correlation with financial recovery. It also shows the excursion during the 1970's "oil crisis".

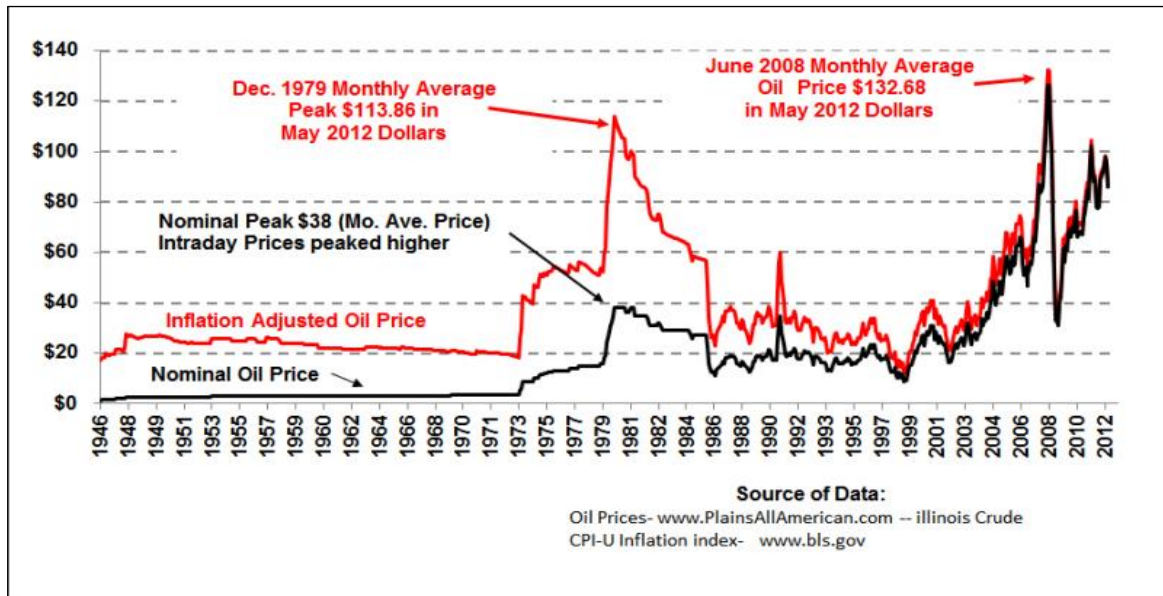
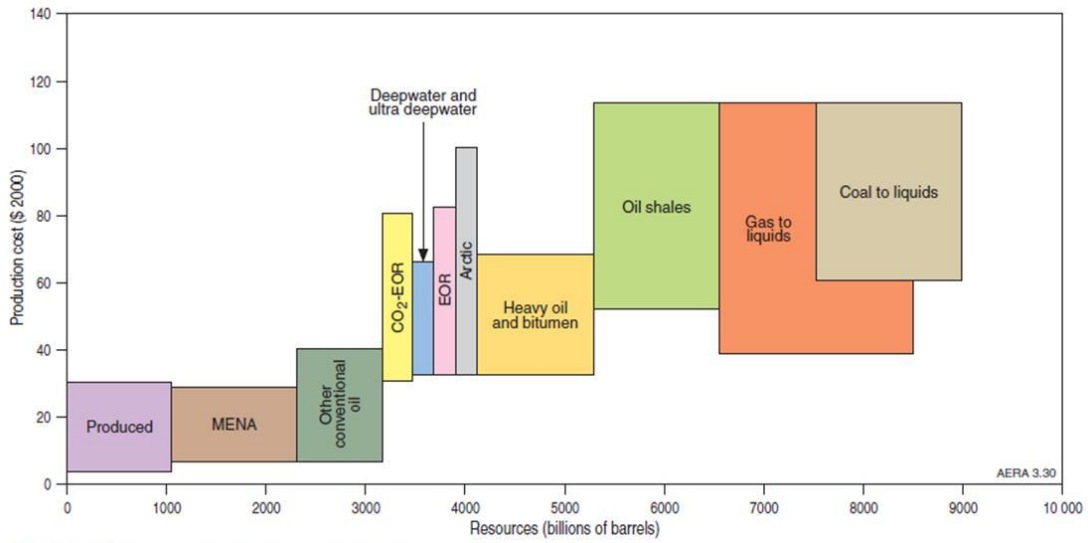


Figure 17: Real and nominal crude oil prices in May 2012 USD reproduced from [www.InflationData.com](http://www.InflationData.com).

There is much debate on the timing of "peak oil" ie the point where demand exceeds supply, increased efforts at exploration and extraction no longer keep pace with the depletion of a finite resource and a growing demand. There appears to be a consensus that at least for "conventional" oil that is within +/- a decade of the present. If that is the case, then the historic price trend can be interpreted as showing an underlying trend to ever increasing prices as demand continues to grow faster than supply. Sudden financial crises can of course reduce such a trend for their duration and market manipulation such as in the 1970s, can have a major impact.

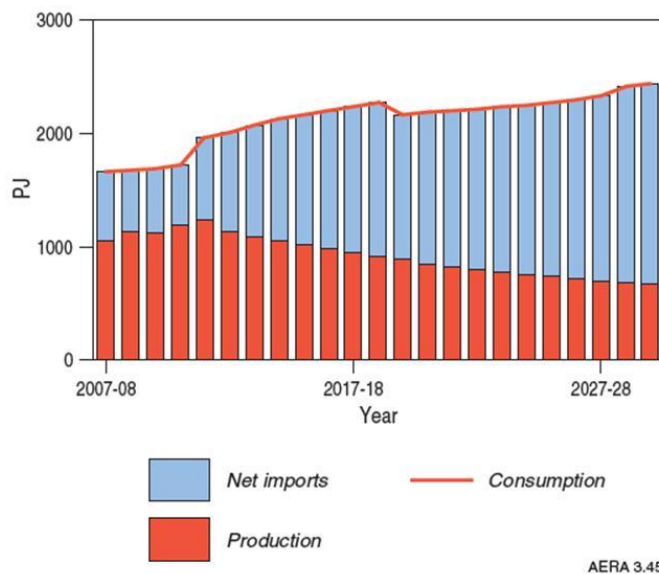
There are a range of technically understood alternatives for supplying oil all of which are more costly than extracting it from conventional reserves. Figure 18 illustrates this as a cost vs volume supply curve.



**Figure 18: Long term oil supply cost curve reproduced from ABARE 2010 based on data sourced from IEA 2008.**

Coal to Liquids and Gas to Liquids figure prominently as being more expensive but of large relative volume. Biomass based solutions are not shown but should also be considered, they are likely to be more expensive but with no net CO<sub>2</sub> production.

Looking at the issue from an Australian perspective, there is the added dimension that our domestic production of oil is declining in addition to our increasing demand (Figure 19).



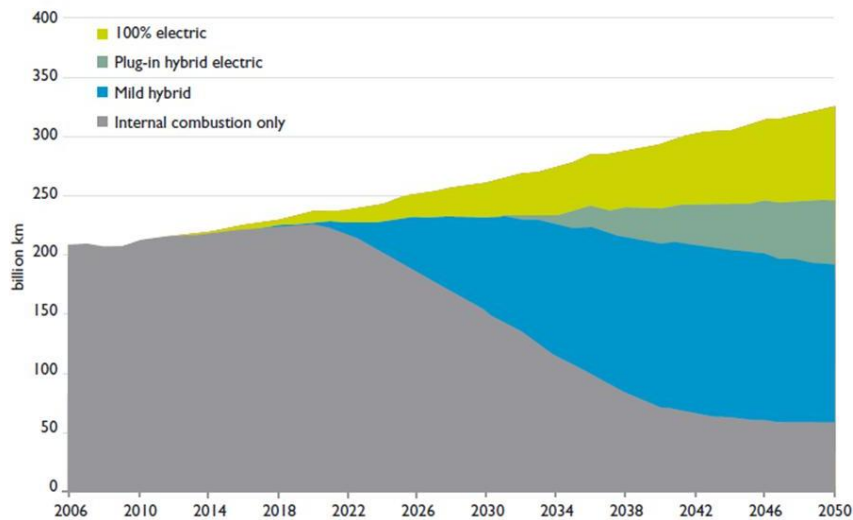
**Figure 19: Australia's oil supply – demand balance outlook, reproduced from ABARE (2010).**

Transport is the major end use for oil. CSIRO have carried out some detailed modelling of future trends in transport energy for Australia. In contrast to Australia's stationary energy sector, transport energy demand continues to grow at 2.4%/year. The transport sector is responsible for 14% of GHG emissions (compared to 50% from the stationary energy sector). 89% of the





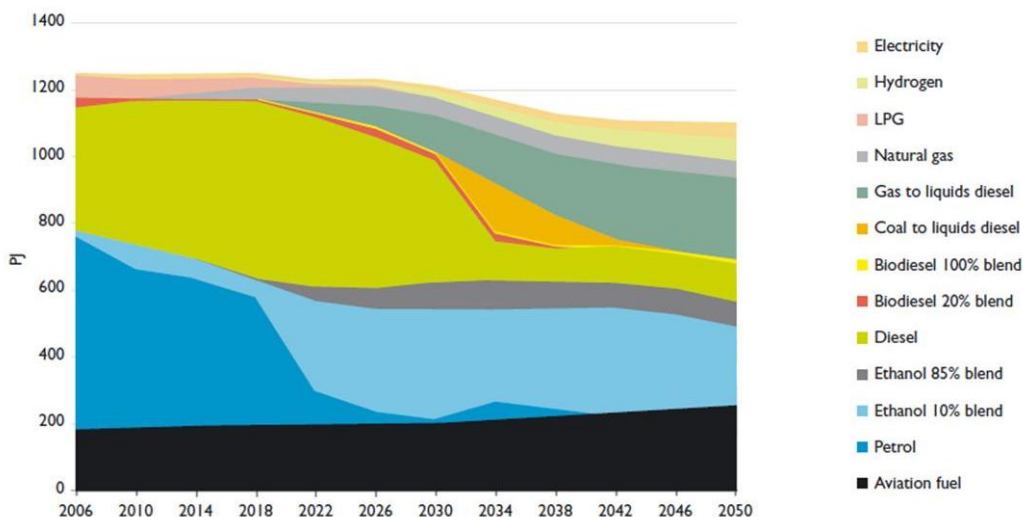
transport contribution is from road transport. One obvious consequence of oil price increases will be to drive an increased use of electric vehicles. Based on their forward cost assumptions, this is indeed a likely result, as shown in Figure 20.



**Figure 20: Projected increasing electrification of road transport for high oil price and 60% below 2000 emission target scenario, reproduced from CSIRO (Graham et al 2008).**

However it can be seen that even out to 2050, much of the transport energy is likely to come from liquid fuel combustion, be it in pure internal combustion vehicles or hybrids or fuel cell based vehicles.

CSIRO has modelled projected shares and effects of high oil prices and emissions reduction scenarios and it shows a declining but remaining substantial share of road transport requiring liquid fuels out to 2050 as shown in Figure 21.



**Figure 21: Consumption of transport fuels under slow decline in oil supply, fast technology response, fuel cell cars available, and 60% below 2000 levels by 2050 emission target, reproduced from CSIRO (Graham et al 2008).**

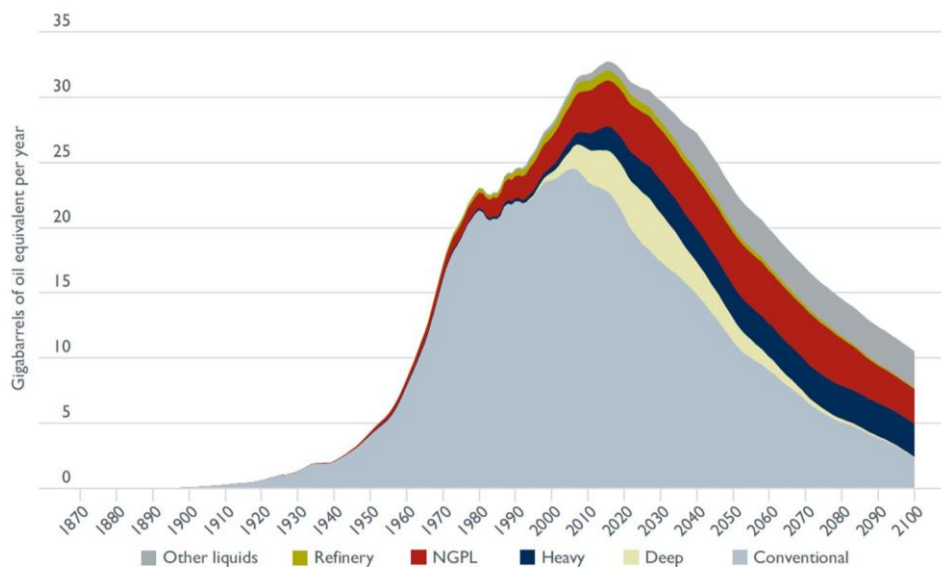
The future mix is very sensitive to assumptions. Note that Coal to Liquids and Gas to Liquids feature significantly. Assumptions around carbon pricing have a major impact.

A relevant study commissioned by the DRET is BITRE (2009), “Transport energy futures: long-term oil supply trends and projections”.

*“For the next eight years it is likely that world crude oil production will plateau in the face of continuing economic growth. After that, the modelling is forecasting what can be termed ‘the 2017 drop-off’. The outlook under a base case scenario is for a long decline in oil production to begin in 2017, which will stretch to the end of the century and beyond. Projected increases in deep water and non-conventional oil, which are ‘rate-constrained’ in ways that conventional oil is not, will not change this pattern.”*

They assess every type of oil source in every world producing region to come up with this conclusion. It is embodied in Figure 22. Essentially conventional oil has peaked, the more expensive non-conventional sources have the effect of postponing the overall peak until about 2020, however those technologies are judged unable to grow fast enough to offset the reduction in conventional oil. This prices should rise quite quickly to a “non-conventional” price, but then continue to rise depending on the demand / supply balance.

The rate limitation, is linked to the cost and practicality of constructing systems and the relatively rapid depletion of individual shale oil wells



**Figure 22: Composition of world future oil / liquid fuels production**

In pure reserves, non-conventional oil is estimated to be larger than conventional oil however the recoverable fraction is lower such that the total recoverable amount is only about a half of what conventional oil is/ has been. It is also limited in the rate at which production can be scaled up due to more difficult environmental and infrastructure constraints.



More recently the IEA 2012 World Energy Outlook (IEA 2012), has identified a major surge in Shale oil production in the USA. Their analysis extends the overall peak beyond 2017, but is nonetheless consistent in principle with Figure 22. It is also not suggested that Shale oil production will lead to any long term sustained drop in prices.

## 12. APPENDIX C: CHARACTERISTICS OF VICTORIAN BROWN COAL

An early analysis by Perry et al (1984) presents the composition and characteristics of Victorian Brown Coal in detail for a range of sites and depths. Considerable variation is identified.

Wosoboenko (2012) in a recent presentation illustrates the composition of Latrobe Valley Brown Coal as shown in Figure 23.

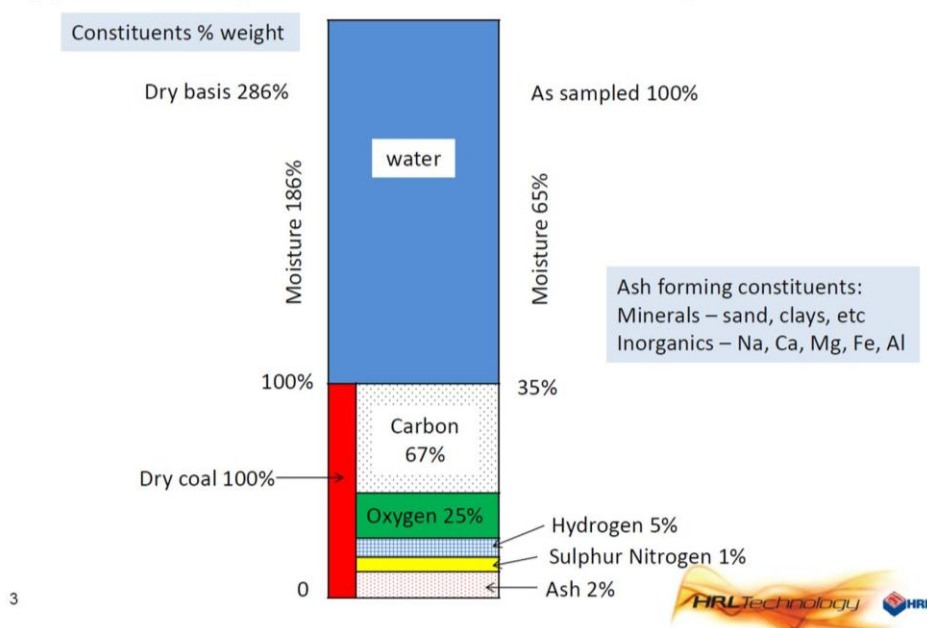


Figure 23: Typical composition of Latrobe Valley brown coal, reproduced from Wosoboenko 2012.

Based on Perry (1984) and others, Some key relevant parameters are given in Table 7.

Table 7: Key parameters for Victorian Brown Coal.

Parameter	Range	Typical / average value
Moisture weight fraction	50%-65%	62%
Gross Dry Specific Energy (GDSE)	25 -27 MJ/kg	26 MJ/kg
Gross Wet Specific Energy (GWSE)		9.9MJ/kg
Net Wet Specific Energy (NWSE)	5.24 – 13.87 MJ/kg	8.5 MJ/kg
H/C atomic ratio	0.77 – 1.16	0.86
H/C mass ratio (based on 1.08 and 12.01 kg/kmol atomic H and C)		0.0773



The Gross Dry Specific Energy (GDSE) is the heat that would be extracted from burning a sample of perfectly dry coal and cooling the reaction products to ambient temperature, with any water vapour assumed to be condensed (sometimes called the Lower Heating Value (LHV) ). If the dry coal is present in a sample that is 62% water by weight, then the Net Wet Specific Energy is simply  $0.38 \times$  the GDSE in reflection of the reduced fraction of combustible material in a 1 kg sample. The Net Wet Specific Energy is lower again by an amount equal to the enthalpy required to vaporise water ( $2.22\text{MJ/kg}$ )  $\times$  the  $0.62$  kg of water in a sample of wet coal.

In many sources that attribute an energy value to brown coal, it is not made clear which of these energy statistics is being used (eg AERA as reproduced in Appendix A). Varying typical values for moisture content are also quoted. In most cases it can be assumed to be the GWSE.

If wet brown coal is combusted in a boiler to heat steam, it is only the NWSE that can be ideally transferred to the steam. If the wet brown coal is internal to a process (eg a gasifier) then the GWSE is the amount of energy released in oxidation, however the water component will form part of the reactant mixture.

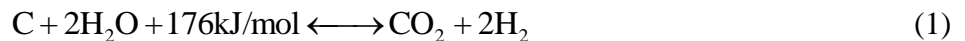
Both the energy content and C/H ratio determine a  $\text{CO}_2$  emission intensity. With  $0.67 \times 0.38\text{kg}$  of carbon in every kg of wet coal, the mass of  $\text{CO}_2$  produced will be  $44.01 / 12.01$  as much, ie  $0.933\text{kg}$  of  $\text{CO}_2$  produced for a release of  $9.9\text{MJ}$  (GWSE), giving an intensity of  $94.4\text{kg/GJ}$  (neglecting emissions associated with mining activity).

Based on a carbon price of  $\$23/\text{tonne CO}_2$ , this means the cost of energy available from wet brown coal is increased by  $\$2.16/\text{GJ}$  over its production cost. Other carbon prices would change the value proportionately.

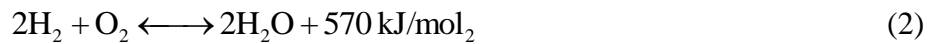
## 13. APPENDIX D: TECHNOLOGIES FOR COAL CONVERSION

### 13.1. Important reactions

As noted above, an enormous range of complex reactions can be expected to operate in parallel. However it is instructive to introduce some of the simpler and more important ones. If a pyrolysis step is assumed to be completed, the product Char is essentially pure carbon. This can be gasified according to:



If the hydrogen were subsequently burnt / oxidized the reaction would be:

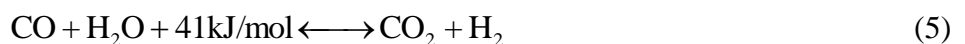
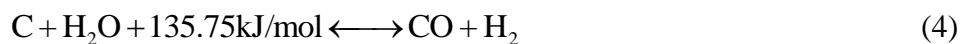


Compared to just burning the coal



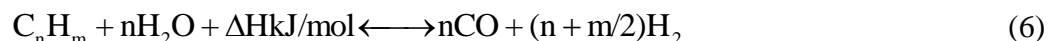
le the enhanced gas contains  $176/570 = 30\%$  extra energy and it can also be applied in much more efficient / high value processes.

The carbon gasification reaction is actually two steps:

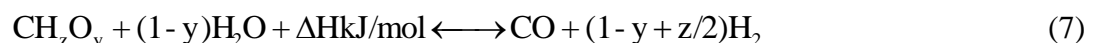


If one stops after the first step (which is the energy intensive one), the CO plus H<sub>2</sub> mix, called syngas, is the feed stock for FT or methanol synthesis or other processes. The second reaction, named the "Water gas shift reaction" must be carefully managed in either direction as desired according to the interest in maximising CO or H<sub>2</sub> in a particular process.

Other hydrocarbons are gasified according to:



And / or:



The energy fraction that is added depends on the C H ratio but will be around 20%.

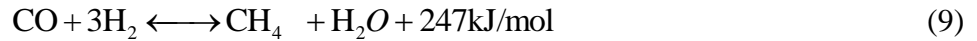


Other key reaction steps are the Boudouard reaction between C and CO<sub>2</sub>:



Which is often an undesirable side reaction.

The methanation reaction:



Which in the reverse direction is the endothermic steam reforming of methane.

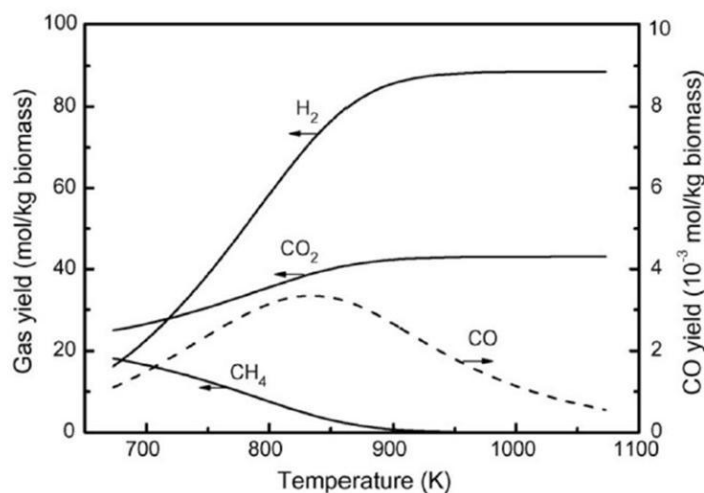
In a Fischer Tropsch reactor fed with a CO / 2 H<sub>2</sub> syngas mixture, the long chain molecules will be built in a variation of the reverse of reaction 6, ie:



With heat being released.

Overall, the conversion of coal to synthesis gas is endothermic, the synthesis of longer chain hydrocarbons is exothermic and the net conversion of coal plus steam to liquid hydrocarbons is endothermic but less so than full gasification.

Equilibrium composition of reaction products from a particular process depends on conditions as illustrated for supercritical water gasification in Figure 24, and Fischer Tropsch reactions in Figure 25



**Figure 24: Equilibrium gas yield from supercritical water gasification with 95 wt % water, as a function of temperature at 25MPa reproduced from Lu et al (2011).**

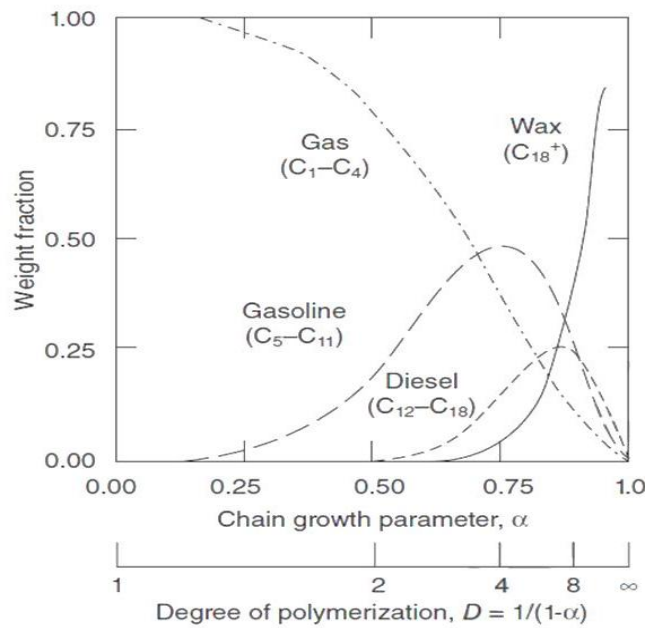


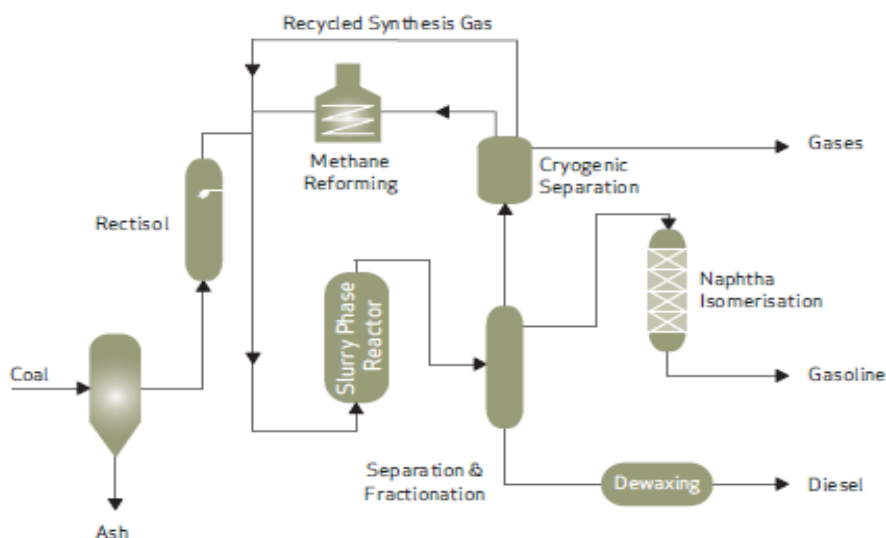
Figure 25: Product yield in Fischer Tropsch synthesis from Perry (2008).

## 13.2. Commercial processes

The most highly developed commercial reactor configurations have historically been established on a proprietary basis by major chemical industry companies. Particular reactor designs are combined with other process details for an overall process design for a particular product.

Fischer Tropsch processes can be either Low temperature (230 - 240°C) or high temperature (300 - 350°C). The Low temperature approach produces a heavier profile of products compared to the high temperature approach. The South African company, SASOL, is a major developer of both approaches.

Source: UK DTI, 1999



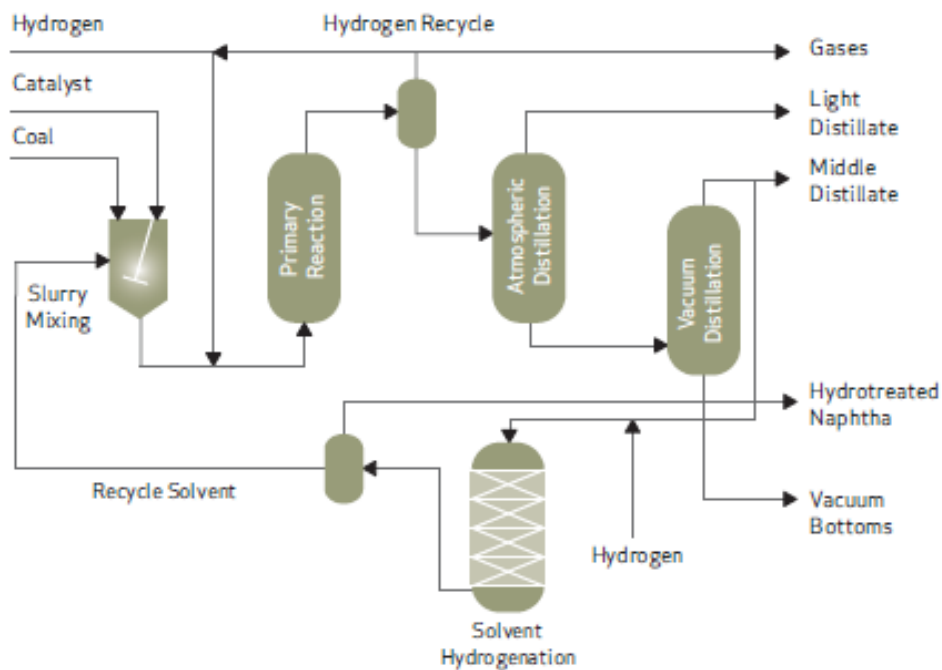




**Figure 26: The SASOL High Temperature Fischer Tropsch process, reproduced from WCI (2006).**

The SASOL HTFT process illustrated in Figure 26, involves circulating fluidised bed gasification coupled to a HTFT slurry phase reactor at 20 - 30bar, 300 - 350°C. Iron based catalyst particles are circulated as a slurry in the inventory of liquid phase hydrocarbon along with a feed stream of syngas. The catalyst particles are recycled as part of the separation / fractionation step. Liquid yields are reported to be in excess of 70% of the dry weight of coal feed and thermal efficiencies are around 60 -70% (WCI 2006).

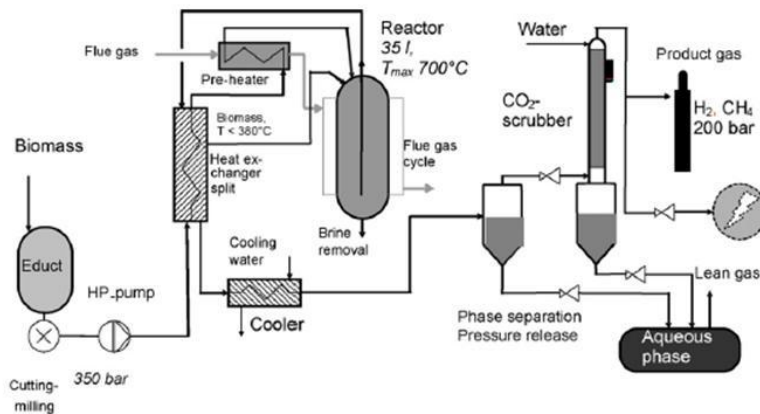
Source: UK DTI 1999



**Figure 27: The NEDOL direct coal to liquids process, reproduced from WCI (2006).**

The NEDOL process (Figure 27) is an example of a more recently developed direct coal to liquids approach. The primary reactor is a slurry phase reactor involving coal and iron based catalyst particles mixed in an organic solvent. It operates at 450°C and 170bar and the products are separated and post processed, with a continuous feedback to solvent supply.

The largest existing pilot plant for SCWG is the “Verena” reactor operated by Forschungszentrum Karlsruhe since 2003. It has a capacity of 100kg/hr, is 3.5m high and 0.11m diameter and operates to 350bar, 973C (Figure 28).



**Figure 28: The VERENA SCWG reactor process from Kruse (2009) via Watson (2012).**

Next generation coal gasification approaches are reviewed by Barnes (2011), as part of an overall consideration of IGCC systems. The range of proprietary new gasification approaches given is:

- “Bluegas™ from GreatPoint Energy – a method for producing substitute natural gas directly from coal and other carbonaceous materials using a single fluidised bed gasifier with an entrained catalyst.
- Calderon Process from Energy Independence of America Corporation – a method for producing dual streams of clean synthesis gas (or ‘syngas’) – one hydrogen-rich, one carbon monoxide-rich – from the staged pyrolysis of coal and other carbonaceous material followed by air-blown slagging gasification of the char.
- Viresco Process (formerly the CE-CERT process) from Viresco Energy – a method for producing syngas for chemicals production and power generation using thermally-forced steam hydrogasification of moist carbonaceous fuels coupled with steam methane reforming.
- HTHG from ThermoGen Hague – a process for producing substitute natural gas from low-rank coal using very high temperature steam gasification without significant oxygen.
- HydroMax from Alchemix – a method for producing synthesis gas from coal and other carbonaceous materials using molten bath technology adapted from the metal smelting industry;
- Wiley Process from SynGasCo – a method for producing synthesis gas from coal and other fuels using pyrolysis, gasification, and non-catalytic syngas reforming at moderate temperature and low pressure without the addition of external oxygen.
- Ze-gen – a method of producing synthesis gas from organic waste and other carbonaceous materials using liquid metal gasification technology drawn from the steel industry.”

As noted earlier, the HydroMax and Zegen ideas are very similar in principle to the molten salt idea of Weizmann institute. Both use molten iron rather than molten salt however.



## 14. APPENDIX E: OPTIONS FOR COAL TRANSPORT

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The possibility of transporting coal to locations of higher solar resource for solar driven conversion can be contemplated. Options include, road, rail and less well known pipeline methods. Transport by ship / barge is quite attractive but not considered relevant here.

### 14.1. Road or rail transport

Assuming existing roads are used, the cost of transporting coal by road is dominated by operational expenses including fuel costs and labour. Road transportation is unsuited to transportation of large quantities of coal due to the size limitations of each truck. It is typically only used as a short-term solution for coal transportation, or where the quantities being transported are very small.

Rail transportation can be an economical solution if a railway already exists. In this case the largest components of the cost are fuel, purchase of trains, and ongoing maintenance costs.

Compared with pipeline transportation, rail transportation has the advantage of requiring no specific coal processing for transport, and no water. It is thus the preferred solution for areas with limited water availability and areas with existing railway lines.

A relevant comparison of the road and rail options for Australian conditions can be found in [http://www.pc.gov.au/data/assets/pdf\\_file/0007/48373/sub041attachmentb.pdf](http://www.pc.gov.au/data/assets/pdf_file/0007/48373/sub041attachmentb.pdf), it suggests that in 2006, rail freight costs fell in the range \$0.025 - \$0.032 /tkm. Road transport costs fell between \$0.045 - \$0.064 /tkm.

### 14.2. Slurry pipelines

Slurry pipelines are an established method of transporting materials over long distances. Coal is crushed into fine particles (up to 1mm in diameter) and mixed with water to form a slurry. The slurry is then pumped through pipes to its destination, where it is dewatered and prepared for use.

Slurries with ultrafine particles (<0.01mm) and a surfactant, do not settle out even when flow is stopped.

The slurrification and deslurrification of the coal is the most expensive and energy intensive component of the coal slurry pipelines. These costs remain fixed regardless of the length of the pipeline; for this reason slurry pipelines are more cost effective over longer distances (300 km or greater) when compared with rail, road or coal log pipeline transport. Slurry pipelines are particularly cost effective when the coal is needed in slurry form, so dewatering is not required.

Coal slurry pipelines require approximately 50% water and 50% coal by weight. A reliable water source is usually crucial to the operation of the slurry pipeline. The Black Mesa coal pipeline in the USA operated for 35 years transporting coal over 440km before suspending operations due to water shortages. It used a single inlet pumping station to inject the slurry at 6,200kPa. However,

existing studies of coal slurry pipelines are for black coal only. Brown coal has a high water content (up to 60%) however this water is physically trapped in the solid particles and needs to be released before it could contribute to the slurry process.

Other Reference projects included:

- MMX, Iron Ore Slurry Pipeline, Brazil, 550 kms
- Da Hong Shan, Iron Ore Slurry Pipeline, China, 171 kms
- Paragominas, Bauxite Slurry Pipeline, Brazil, 244 kms
- Samarco, Iron Ore Slurry Pipeline, Brazil, 396 kms
- Simplot, Phosphate Pipeline, USA, 100 kms
- New Zealand Steel, Irons and Concentrate Pipeline, New Zealand, 18 km
- Los Pelambres, Copper Concentrate Pipeline, Chile, 120 km
- Minera Alumbraera, Copper Concentrate Pipeline, Argentina, 310 km
- Jianshan, Iron Ore Slurry Pipeline, China, 100 km
- Minera Dona Inés Collahuasi, Copper Concentrate Pipeline, Chile, 203 km
- Freeport, Grasberg Mine, Copper Concentrate Pipeline, Irian Jaya/Indonesia, 120 km
- Batu Hijau, Copper Concentrate Pipeline, Indonesia, 18 km
- Hy-Grade Pellets, Iron Ore Slurry Pipeline, India, 268 km

### 14.3. Coal log pipelines

Coal log pipelines require coal to be compacted into “logs” for transport through pipelines using water. Water requirements are lower than for slurry pipelines, with about 30% water by weight required. A key advantage of coal log pipelines over slurry pipelines is that dewatering at the end point is not required, and the logs are ready for transport by another means (for example export by ship or truck transport to a number of destinations). Compared to coal slurry pipelines, coal log pipelines require a higher-cost lined pipe and additional pumping stations to maintain the correct coal log velocity.

Given the high water content of brown coal, it may not be practical to compact it into logs as with black coal.

### 14.4. Comparison

The unit costs of coal transportation by rail, road and pipeline are compared in “Economics of Coal Log Pipeline Transporting Coal” by Liu et al (1998). The costs presented include capital costs, operational costs over the project lifetime, and investor profit.



For high coal throughput over a distance of 1000km, the cost comparison is given in Table 8.

**Table 8: Cost comparison of transportation of coal by different methods over a distance of 1000km**

	Road	Rail (existing railway)	Coal Slurry	Coal Log
\$/t for 1000km (USD 1994)	80	15	15	12
\$/t/km	0.080	0.015	0.015	0.012
esc 1994 to 2012 at 2.5%/yr	0.125	0.023	0.023	0.019
\$/GJ/km	0.0125	0.0023	0.0023	0.0019
\$/GJ for 1000km	12.5	2.3	2.3	1.9
\$/GJ for 500km	6.2	1.2	1.2	0.9

Comparing this with a 2006 report

([http://www.pc.gov.au/data/assets/pdf\\_file/0007/48373/sub041attachmentb.pdf](http://www.pc.gov.au/data/assets/pdf_file/0007/48373/sub041attachmentb.pdf)) which compares road and rail costs for two major long haul routes in Australia and finds Rail costs are \$25 – 32 \$/,000tkm and road \$45 -64 ,000t/km.

Liu (2006) presents an example cost calculation for an 81 mile slurry pipeline and the same coal log pipeline noting that due to the short distance the slurry pipeline would be less cost effective than a coal log pipeline. Coal log pipelines are considered most appropriate for distances between 50 and 200 miles.

A coal slurry pipeline over this distance is expected to cost approximately \$31/MT/yr capacity to construct, with the largest components of the cost being slurry preparation and dewatering facilities. By comparison a coal log pipeline over the same distance costs \$13.4/MT/yr capacity, with the largest components of costs being construction of the lined pipe and preparation of the coal logs.

Rail costs do not include the cost of building a new railway line. According to other studies such as *The Direct and Indirect Energy Costs of Coal Transport by Alternative Bulk Commodity Modes* (Zuchetto et al, 1980), construction of a new railway line drastically increases the cost of transportation by rail (by a factor of about 10), making it uneconomical compared with other methods. However a more appropriate approach would be to include an appropriate allocation in proportion to the fraction of total rail line capacity that coal shipments occupied.

### **Comparison of energy requirement of pipelines with rail transport**

When comparing the energy requirements of different transportation mechanisms, there are three aspects of transportation systems to be considered.

- Direct fuel and labour costs for operation of the system

- Indirect costs generated by construction, replacement and operation of the system (eg energy required to produce steel for barges, concrete, etc.)
- Induced effects caused by a transportation system (eg, a new highway creating residential growth; a long term change in land use caused by allocation of water resources etc).

A comparison of life cycle energy requirements of coal transportation by barge, rail and slurry pipeline is made in *The Direct and Indirect Energy Costs of Coal Transport by Alternative Bulk Commodity Modes* (Zuchetto et al, 1980). Since barges are not a viable method of transporting coal from the LaTrobe Valley to inland Australia, we have only considered rail and pipeline transport in Table 9.

**Table 9: Energy requirements of transporting coal over 1000km, assuming brown coal energy content of 10GJ/T**

Transport mechanism	Rail transport (existing railway)	Rail transport (new railway)	Pipeline
Energy requirement (MJ/T km)	0.37	2.62	0.56
Percentage of available coal energy	4%	26%	6%



## 15. APPENDIX F: COMMERCIAL CTL PROJECTS

Without performing a thorough review of proposed CTL projects, a brief sample of some that are discussed in the public domain provides an indication of the status of the sector.

- <http://www.aaas.org/spp/cstc/briefs/coaltoliquid/> notes that
  - *“China’s ShenHua group began operation of worlds first direct CTL facility in December 2008.”*
- [http://en.wikipedia.org/wiki/Coal\\_gasification](http://en.wikipedia.org/wiki/Coal_gasification) Reports that:
  - *“The Great Plains Synfuels Plant has been operating in Beulah, North Dakota since 1984. It produces synthetic natural gas from lignite.”*
- In regard to projects in Australia, <http://www.processonline.com.au/articles/56586-Cutting-time-to-market-of-coal-to-liquid-energy-projects> reports that:
  - *“CTL Projects owned by Ambre Energy, Syngas Limited, New Hope Coal, Altona Energy, Linc Energy, Coalworks, and others are all in progress in Australia, but time to market and R&D costs are concerns.”*
- WCI (2010) suggests:
  - *“Linc Energy are currently investigating the potential for a CTL project in Queensland, Australia. Here the coal will be converted to syngas while ‘in-situ’ or underground by an established process. This method has the potential to reduce capital costs significantly, as the costly surface gasification step is removed. Underground Coal Gasification (UCG) has been taking place at the site since 1999 and is the largest UCG project outside the Former Soviet union. In 2006 Linc Energy announced plans to expand the Chinchilla project to include the production of CTL fuels and electricity from the site. The production target of the CTL process from the Chinchilla site is 20,000 barrels of diesel fuel per day – approximately 10% of Australia’s needs.”*
- Established in July 2009, Ambre CTL Limited is proposing the nation’s first commercial scale coal-to-liquids project at Felton in south east Queensland although <http://www.ambreenergy.com> has little reference to the CTL project
- <http://www.syngas.com.au>:
  - *“The Clinton Project is located approximately 120 km northwest of Adelaide city, in South Australia, as shown in Figure 1 below. The Project involves the development, commissioning and operation of a large scale, long-term premium diesel production facility. Syngas is targeting bringing the Clinton Project online in 2015 and operating it for 40 years The Clinton Project’s primary feed material is*



*the Company's 100% controlled feedstock within Mineral Exploration License (MEL) 3896. This coal (lignite) feedstock is currently expected to be supplemented by non-food biomass sourced from the local area as part of the Company's carbon management strategy. Technically, the Clinton Project is what is called a Coal-Biomass-to-Liquid (CBTL) project"*

- New Hope Coal ([http://www.newhopecoal.com.au/media/6686/ctl\\_em\\_plan\\_v21.pdf](http://www.newhopecoal.com.au/media/6686/ctl_em_plan_v21.pdf)) Is planning a pilot plant on queensland.
- <http://www.coalworks.com.au/projects-oaklands.php>
  - *"Preliminary Feasibility Studies assessing a range of CTL plant capacity options (7,000, 14,000 and 21,000 bpd), as well as other value adding options (eg Coal to Plastics) is underway."* *"The Oaklands North project in southern NSW"*
- Altona energy <http://www.altonaenergy.com/> are the proponents behind the Arckaringa coal to liquids project in Northern South Australia







## **IT Power Renewable Energy Consulting**

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