Practically Carbon Free

Resourcing civilisation whilst restoring the planet
A paradigm and workable plan for a low carbon future

Jonathan Lee
Trinity College, Cambridge

Original: 4th August 2008
Latest revision: 3 November 2008

One of today's greatest challenges is to find a way to fulfill the ever-growing needs of mankind for energy, in a manner that is sustainable, dependable, non-polluting, and economically viable, whilst also being carbon-free, and resistant to current fossil geo-politics.

There does not seem to be a silver bullet that addresses all these issues. However, this document presents an alternative way of considering energy production and usage, in order to examine the "whole of cycle" issues. When problems are considered thermally rather than in energy terms, a new range of possibilities open up based largely on existing technologies, but delivering a range of pragmatic, planet-friendly solutions for industry, transport and power production.

Index

0 Prerequisites

For reasons of brevity, this document is incomplete in the sense that many scientific facts and statements of current reality are assumed to be known / understood. Standard literature/web searches can be used to fill these gaps, and some references are provided
The reader is assumed to have a good working knowledge of …

- Science, especially Energy and Entropy
- The nature of Thermo-Chemical and biological cycles
- Nuclear physics and reactors
- Economics

Without this knowledge base, little of the document after the Executive Summary will make much sense.

For an initial look over many of these issues, alongside general energy policy, 'Sustainable Energy – Without the Hot air' by David MacKay is strongly recommended. It should be noted that his discussion focuses more on what is technically possible, rather than necessarily a publicly acceptable approach, and so this document disagrees with some of his conclusions.

Axioms

These set a framework for further discussion, but will not be justified here.

- Terminal energy use per person will not fall significantly, if at all, and the global population will continue to rise
- Consumer behavior will not change significantly to improve efficiency, so primary energy use cannot be **relied** upon to fall
- Any proposed solution or mix thereof must cover all expected energy use
- Whole cycle analysis must be used; behavior of a solution solely at point of use is pointless and misleading.
- Physics and Statistics must be respected; Economics cannot be ignored.
- CO_2 emissions are a primary problem to be dealt with
- Any proposed solution must be practical, preferably over a gentle transition from current reality

These are chosen to be both pragmatic and support a quantitative discussion. Demanding what could be seen as "Lifestyle Changes" is unlikely to be politically feasible, and so behavior changes are excluded as a viable approach.

Assertions

1. The major energy uses are
    - Generation of Electricity,
    - Transport … petrol in cars, diesel in trucks, and kerosene in aircraft,
    - Heating
    - All General Industry, including (but not limited to):
        - Construction (cement)
        - Iron and Steel
        - Aluminium
        - Agriculture (nitrate fertilisers)
2. Fossil fuels should be saved for use in plastics and lubricants rather than burnt as an energy source in the short term. In the long term, fossil fuels should not be mined for sustainability reasons.
3. Long term reliability of energy supply is essential
4. Minute by minute reliability of the electricity supply is essential
5. The free-market will create solutions provided that they are economically sound, and not politically hindered
6. Many so-called "Green" solutions are neither sustainable nor eco-friendly, when considered over the whole cycle, e.g. current Hydrogen production uses Natural Gas, and Bio-fuels use energy intensive nitrate fertilisers
7. Any useful solution must be Carbon neutral over the whole cycle. Furthermore is should be sustainable over the extreme long term (1000 years)

Units

MW	Mega-Watt – a unit of power
GW	Giga-Watt – a unit of power
GWh	Giga-Watt Hour – a unit of energy
GW_{th}	Giga-Watt Thermal
GW_e	Giga-Watt Electrical

1 Executive Summary

Energy consumption is considered within the constraints of apparent climate change. Practicality and whole cycle analysis are used as the metric for potential solutions. Replacement of backbone electricity generation with conventional renewables is rejected due to grid requirements for reliability, and the attendant problems in backup generating capacity. Fossil fuels are rejected for their emissions. Nuclear power is proposed as an alternative source of reliable thermal energy, with potential use in electrical generation.

Alternatives to fossil fuels in transportation are discussed. Thermo-chemical production is proposed over electro-chemical or biological methods due to both scalability, and efficiency with regard to entropy. DiMethylEther (DME) is proposed as a primary transport fuel due to ease of synthesis and constraints on large-scale usage.

Certain synergies between thermo-chemical fuel production and responsive supply are noted. Exploitation of this is proposed to allow greater traditional renewable penetration into a grid mix, should the market select for them.

- Molten Salt Thermal Reactors (MSTR) are proposed as a practical, high efficiency, high safety reactor design. Furthermore, MSTRs are considered as thermal sources rather than electricity generators.
- Thermal sources have the ability directly to produce long term sustainable Hydrogen or electricity.
- A “Combined Hydrogen and Power” (CHyP) reactor could rapidly vary its electricity production and make the electricity grid not only stable, but also able to accept unpredictable solar / wind power.
- The transition from nuclear electric power to nuclear heat rapidly reduces the need for fossil heating without compromising efficiency.
- MSTRs are proposed as safe, high temperature heat sources for industry
- Thermal plants enable a range of carbon neutral industrial processes, such as production of Iron and steel , Aluminium, Nitrate fertilisers
- Using thermal plants, fuels (both synthetic petrol and synthetic aviation fuel) can be produced that are compatible with existing vehicles, whilst being carbon neutral across the cycle
- Politicians need to be educated in order to allow the deployment of MSTRs

2 Background Issues on Sources of Energy

Energy Usage

Energy usage in the western world is primarily in three forms.
These are:

- Electricity,
- Thermal heating,
- Fuels for transportation.

Industry uses a combination of the first two, and thus does not need to be specially analysed here.

Electricity is largely produced from thermal cycles driven by fossil fuel combustion, although nuclear heat is also used, alongside small quantities of wind, wave, solar, hydro and bio-mass.

Thermal heating is privately generated from electrical heating or fossil fuel combustion, and in industry again either electricity or fossil fuels are used.

Currently, transport fuels are almost entirely fossil in origin, although proposals for Hydrogen fuelling or bio-ethanol have been made.

Peak and Mean Power Output

For long-term energy balance purposes, the only relevant number is the mean power output, as this is the power extracted to a grid or used in fuel production or some other industrial process. By contrast, the usual quoted figure for the output of a plant is its peak output, as this determines the sizing of the infrastructure required to support it.

This dichotomy leads to significant problems. The mean output of the largest proposed renewable sources, wind and solar, are around 25% of their peak output. On the other hand, backbone coal and nuclear power stations can run continuously at over 90% of peak output.

As a result, any attempt to use these renewables for a significant portion of energy production will have to be concomitant with an increase in grid capacity of a factor of 3 to 4. This requirement (i.e. extra cost) is in addition to those imposed by the extensions for a secondary electricity market, as discussed later.

Grid Stability

National electricity grids must match supply to demand on a minute by minute basis to prevent brown-outs or over-voltage. All grids achieve this by having small quantities of controlled, rapidly throttling production to even out small variations in demand, whilst the larger quantities of generating capacity throttle over a longer period to follow baseline load. The fastest responders are pumped storage systems, which are limited in capacity by geography. The next fastest are gas turbines, clearly problematic due to their CO_2 emissions.

In this context, currently proposed renewables have severe problems. Power output from Wind and Solar varies unpredictably minute to minute, and this would overwhelm the response abilities of most grids. As a result, developers of large wind farms have often also built co-located gas turbines to ensure that most of their variability is removed on-site.

Wave power is predictable and can be used, but it requires the building of demand around the lunar 24.8 hour cycle. This effectively requires that industry pulse production at a similar rate, as domestic consumption is unlikely to vary at this rate.

Hydro and Bio-mass are both controllable, and can thus easily be built into a grid. On the other hand, Hydro produces large quantities of methane (a vicious green-house gas) as a by-product of anaerobic decomposition in its reservoir, and is limited by geography. Bio-mass requires the use of very limited arable land to produce its source crop. Unless agriculture is made to be carbon neutral, then bio-mass has carbon emissions in a whole cycle analysis.

Energy Storage

Effective and efficient energy storage would allow renewables to be an appreciable part of the grid. However, problems arise in efficiency, with the only significant and efficient store being pumped storage. Current UK pumped storage can only achieve 5% of grid output for a few hours. It is noteworthy that over half of existing pumped storage is strategically saved for restarting the grid after a blackout, and few suitable geographical locations exist for additional capacity. Molten salts provide a far more volume efficient energy store, but can only store thermal energy directly. They are still limited by the magnitude of the variations. 60% of the UK's electricity alone for a week constitutes around 45 Million tons of molten salt, at around 0.1MWh/ton.

Quantitatively, the UK electricity grid delivers around 45GW mean. If we had 60% renewables, then a variability of output of even 10% of the grid would lead to 2.7GW of excess/deficit power on a minute to minute basis. This is effectively turning several major power stations on and off on a whim and demanding that the grid can cope. In reality the variability is very much more than this - as shown by the 2006 heat-waves in California, during which the entirety of their wind turbines averaged less than 5% rated output for over a week. Similar statistics are found in the 2003 European heat-wave for Germany and Denmark. It is clear pragmatically that backup generation must exist for renewable sources. Furthermore, since backbone generation cannot be started on a whim, this “backup” capacity must be running continuously. This substantially undermines the ecological case for wind or solar as their backup plants are very inefficient when operating at far below their designed production level.

Bio-fuels

Bio-fuels have been proposed as an alternative to fossils for transport. Whilst this has been successful in Brazil, and widely touted in the West as a means to keep business-as-usual going, there are a range of awkward problems associated with it. Clearly, it requires that high-energy crops be grown. In practice this has meant some form of sugar crop, although corn has also been proposed, with subsequent conversion to short chain alcohols, normally ethanol, by some variety of bacteria or fungus. In the case of sugar crops, the initial problem for the West is that only small areas of the planet can efficiently grow sugar cane. Most Western agricultural sugar comes from beet which has a form of sugar that is harder to extract, with similar problems for corn. Using beet or corn, the energy required to extract the sugars is significant in relation to the energy content. Furthermore, these crops also worsen the fundamental limit of arable land on the planet, particularly given a growing and developing world population, which has also rapidly increased the demand for crops and meat, and thus (indirectly) vastly increased the demand for arable land.

Furthermore, the process is somewhat limited in the fuels that it can produce, as all of the involved chemistry takes place (essentially) at room temperature – with all the restrictions and inefficiencies that are thereby incurred in entropy terms.

A reliable generator is one that can be relied upon to produce an agreed amount of power at a specified future time in (say) the next fortnight. An unreliable power generator is any that cannot give this guarantee. Unreliable is thus effectively the same as unpredictable.

Historically all UK base load power stations have been reliable since break-downs are rare, and the grid has been robust.

However, in this context, an unpredictable / unreliable generator means any plant that may be unable to deliver power for any reason e.g. cloudy, or no wind, and these events happen much more frequently than grid failure or mechanical breakdown.

3 Renewable Sources of Energy

If we consider just electricity, then the UK alone consumes a time-averaged 45GW of power. In the absence of significant energy storage systems, generation must match this consumption from ***second to second*** to prevent a grid from going under-voltage. Failure to do this is the fundamental cause of large area black-outs, as have struck the US and continental Europe in recent years. Both of these failures were caused by a single station dropping output for less than a second.

Any significant drop in output for as little as half a second will cause grid problems because grid generators use the grid itself to energise their alternators. Consequently, a small drop in grid voltage will reduce the power generation of every generator in the grid, starting a vicious downward spiral. Therefore, a drop in voltage in the grid is always very problematic on a large scale, leading rapidly to large-scale black-outs. This has huge knock on consequences for many renewables, which, in the grid sense, are unreliable sources of power

As a result Wind, Wave, Tidal, Solar PV and Solar Thermal power all cause problems whenever they provide a non-trivial proportion of the energy on a grid due to their variability, which the grid sees as unreliability. Yet the requirement placed on the Grid is to maintain output (voltage and power) from second to second.

Tidal

It is clear that the size of the tides is essentially predictable, even with the effects of storms, a few hours ahead of the tide. As a result, variation in power output of tidal systems can be predicted and absorbed by the current grid, with its large backbone of coal and nuclear which can be throttled to adjust over a few hours.

By contrast, if such an absorption capacity were absent from any proposed future generation mix, then tidal energy could not be efficiently utilised, as potential generation would have to be wasted to prevent grid over-voltage. Whenever a given tide is below expectation, then lacking such an absorption capacity would lead to grid failure in short order. Hence if some level of backbone generation is not maintained, then tidal energy is problematic.

A further complication is that the tides follow a (circa) 12.4 hour cycle (lunar cycle of 24.8 hours with two tides per lunar day). Hence the times at which the tides provide power drift day by day, and thus move with respect to demand, further meaning that other generation will have to vary rapidly to take over when tides are producing power during periods of low demand.

Solar Thermal and Photo-Voltaic

Similar issues exist. Whilst Solar follows a 24-hour cycle and thus will have a consistent relationship to demand, this relationship is not optimal. Demand generally peaks around 6 or 7 pm, and hence other generation needs to work around Solar, which peaks around midday. Even so, solar PV or thermal has issues of variability, as clearly local weather conditions change from minute to minute. Hence, a great deal of short-term responsiveness must exist in the grid to ensure that over or under voltage does not occur. In the *current* grid, the only sources of such responsiveness are gas turbines and pumped storage. Note that the majority of pumped storage is reserved for restarting the grid from black-out.

Wind and Wave

These have further problems. Clearly neither wind nor wave power follow an overwhelming short period cycle. However, both suffer from significant short-term variability due to local weather conditions in an essentially unpredictable fashion. Hence again a significant quantity of short-term responsiveness in backup must be required or large-scale energy storage must exist. Considering data from recent Californian heat-waves where generation capacity for all wind in the state dropped to 4% rated capacity over a week, it seems reasonable to contend that backup capacity must exist and be startable on short notice. Again, only gas turbines currently fill this role.

Considering the remaining few proposed energy sources, namely hydroelectric, geothermal and bio-mass, we see that they behave far closer to the ideal backbone generators. Hydroelectric is throttleable in 30 seconds, whilst geothermal and bio-mass are both limited to tens of minutes. They have alternative hard limits however.

Hydro and Geothermal

These require specialised geography to operate, and in the former case sites are generally already utilised for power, pumped storage or reservoirs. Hydroelectric power also has problematic failure mode since populations are generally concentrated on valley floors. Dam collapse, whilst rare, is deadly on a large scale. Geothermal has the obvious issue of requiring large masses of hot rock under the surface, and is thus only sensibly efficient in active regions such as Iceland. For the UK, neither seems plausible as a large-scale energy source.

Bio-mass

Bio-mass has clear issues in requiring large quantities of arable land, which is rapidly becoming exhausted by rising populations. It should also be noted that fertiliser manufacture inherently relies on the Haber-Bosch process for production of ammonia for nitrates. This process is very energy intensive, and consumes 2% of global energy consumption. Clearly for bio-mass to claim a green status over the entire cycle it must power its own fertiliser production, which reduces the marginal energy production significantly. Further overheads in agriculture make bio-mass, and the comparable proposal of Bio-fuels, marginal producers at best. If bio-mass is done via production on poor land, then it doesn't directly impact on the shortage of arable land, although potential issues in fertiliser and energy usage make them poor choices for mass energy production.

Conclusion

Looking at the totality, it seems inevitable (if regrettable) that traditional green energy sources are not viable contenders for large-scale integration in a current grid. Proposed alterations to the generating mix to reduce carbon emissions worsen the situation by reducing the responsiveness of the grid, by removing coal and gas generation from the mix. Hence current green energy sources cannot supply electricity demands efficiently, and make no contribution to the demand for fuel and heating.

4 Impact of Generation Uncertainty on a National Grid

In the electricity market, there is an evident risk of local or widespread blackout. Clearly, the cost of such a failure is directly borne by the consumer, who suffers the cost of lack of electricity. In the current UK market, however, the level of risk is determined by the central electricity board, which then demands assurances from suppliers that this risk level be maintained. This is usually achieved by having some internal backup capability, or in principle via insurance from other suppliers, in a secondary market. Given that most current suppliers have few “unreliable” power sources, this secondary market is essentially non-existent, especially since most generating companies do their own backup.

Electricity is currently bought by the board ahead of time for a given time slot. If demand unexpectedly exceeds predictions, or transmission problems occur, then the board again approaches the market for short-term power. Given this, reliable large plants can be throttled slowly to maintain efficiency, and the generating capacity positioned to react to expected demand. Hence reliable plants know their required generation and can achieve it with both very low risk and high efficiency. Known rapid changes in demand are not normally a problem, as pumped storage and other rapidly variable plants can profit by selling less electricity before the demand spike and more after. As a result the makeup of supply changes during rapid demand changes, with the throttleable plants absorbing the change in demand.

For any unreliable plants, however, insurance will be vital. Whilst the mean power production of a wind or solar power station is around 25% of peak over time, on a minute to minute basis significant variability exists. Hence, the commercial cost of these plants is dependent on the price of insurance of supply. Clearly, such insurance will cost at least the market value of the expected quantity of electricity that will be needed; if 100MWh will be needed 10% of the time, then the extra insurance will cost at least that of 10MWh of electricity at that point in time. In reality, the extent of the extra cost above that of 10MWh will depend on the generating mix. If there is a large degree of competition amongst quick throttling power plants, then the extra cost will be low. If, on the other hand, the majority of capacity is in the form of large baseline generating plants, then the cost of this insurance will be very high, as the capability to react to the short term call for extra power by the non-reliable plants will not actually exist in the generating mix. Since currently the largest rapidly varying power plant type are gas turbines, which will need to be reduced in number in the long term, it is likely that this backup capacity will be very expensive.

In a perfectly efficient market, the cost of electricity to the consumer would be the weighted average of price with respect to generating uptime of the generating plants. Hence, wind and PV with their 25% peak utilisation average will only be efficient in the market if they are 4 times cheaper than their competitors for a given maximum load. Of course, given the non zero cost of the involved risk, these sources would have to be cheaper than the stated factor of 4. This significantly worsens the economic case for these “unreliable” plants.

Further issues exist due to the hard limits of an electricity grid. If any given transmission line attempts to carry a current above its maximum, it will overheat, sag and short. In this case, the only practical solution is to cut the line from the grid, which will be likely to overheat another line unless the total current being carried falls. Hence the model of insured generation is inherently more costly, as the transit grid must allocate transmission cable to both the primary and backup generators, unless the primary and backup generation are co-located. In the latter case, only a small number of plants can insure the capacity of any given unreliable source, so the price will be higher. If on the other hand, two sets of cable are allocated, then the grid is vulnerable to failure unless it has massive over-capacity, which is simply not true in the current or currently proposed grid. Furthermore, to ensure that the grid does not fail, all possible combinations of primary or backup generators across the entire network must be considered. If generation must be co-located, then the reliable backup plant is also limited in the maximum required power from it, and its responsiveness, and so in the current market will likely be a small gas turbine. Indeed large wind facilities in Australia have already built new gas turbines to provide backup generation.

Hence barring massive alteration to the grid, all unreliable plants will have to co-locate with backup generation or the electricity board will have to pass on the risks of the generation to consumers. In this case, houses could be equipped with smart meters such that if a given producer fails to make its required level of power, some number of its consumers are blacked out or have their current consumption capped at the meter to prevent grid failure. This would allow consumers to choose their level of reliability, along with the level of 'greenness' of their electricity and its cost. Whilst very unconventional, it does allow a large renewable presence in the grid without attendant backup generation.

If however, the grid is upgraded to the point where it can cope with non co-located backup generation, or backup is built with unreliable plants, the backup must still be able to vary their electrical output on a minute to minute to make up shortfalls. In the current grid, the only such generators are gas turbines, clearly not a desirable option in terms of carbon output. If their fuel has been produced from atmospheric CO_2, it is less bad, but in terms of efficiency it would seem more reasonable to directly use the output of the fuel producing plant. At this stage CHyP cycles become highly attractive, as the slow throttling heat source is not throttled, with only the usage of the produced heat varying from Hydrogen production for fuel to electricity for immediate consumption. This would allow greater use of unreliable renewables in the grid mix.

5 Observations on Thermal Power Systems

Entropy and Efficiency

We have established that non-thermal energy (Wind, Wave, PV and Hydro) cannot supply the bulk of electric and heating energy required, and that Bio-fuels alone will be hard pressed to produce all fuels consumed. We must now consider thermal cycles. Currently these are primarily fossil fuels and nuclear power, although solar concentration has been proposed.

In terms of efficiency, these cycles appear to have far worse ratings than their non-thermal cousins. This is due to the limits imposed by the basic physics of “entropy”, which prevents total utilisation of heat in any form. Operating over a larger thermal gradient lowers the losses due to this. Given that waste heat is normally dumped close to but above room temperature, a larger thermal gradient implies a higher peak temperature in the cycle. This is one reason for gas turbines being more efficient than their coal-fired rivals, and the rationale for integrated gasification in so called 'clean coal' plants. At the same time, Combined Cycle plants seek to lower the output temperature, and thus again improve efficiency. Electricity can be considered (at an individual electron level) as a millions of Kelvin thermal gradient, and thus turning heat into electricity always appears to waste energy, as the entropy content of the electricity is very low for its energy.

If we discard consideration of fossil fuels since they emit CO_2 over their cycle (Carbon capture and sequestration will be discussed later), then we need only to consider Solar thermal and nuclear. Solar in this case is typically limited to low latitude sites, unfortunately a long distance from most consumption, and thus the output can only efficiently be transported as electricity. Unfortunately, this effectively drops useful output by a factor of 2 to 3. Whilst in principle for thermal uses this could be recovered by using a heat pump[↓] driven by electricity rather than direct heating, in practice this is not done, and making the change will take a long time. Other geopolitical issues also obstruct the generation of power in different areas to its consumption.

Ideally, thermal cycles would operate over extreme thermal gradients to maximise efficiency, and would preferably be used to drive processes other than electrical generation if possible, to maximise useful output. On the other hand, they can produce electricity efficiently if the thermal gradient used is large, and the entirety of the gradient is utilised effectively.

Thermo-chemistry

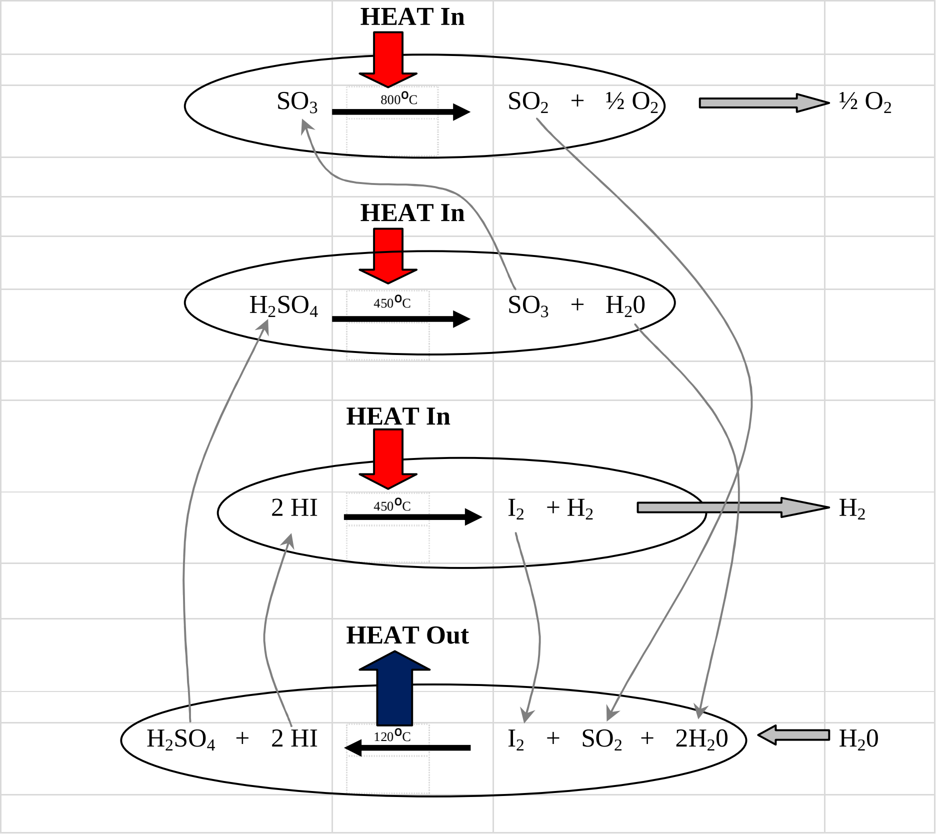
If high-grade heat is produced by the heat source in a thermal cycle, then a variety of useful chemical processes can be driven by it. Given that chemical bonds hold entropy and energy, a $6GW_{th}$ plant that drives chemistry could produce far more energy than the $2GW_e$ that could be scavenged from it. However, this requires temperatures above those typical for a steam cooled plant, and thus are not considered for current thermal generation plants. Solar concentrators could theoretically do this, but could not be built in the industrial plants where the heat would be consumed.

[↓] Heat pumps are always a good idea to replace electrical heating/cooling, though they seldom feature in the design of UK homes. An electrically driven heat pump combined with a ground heat exchanger will often deliver 4 times the thermal efficacy compared to the electrical energy used.

The Sulphur-Iodine Cycle

This is an alternative closed-chemical-cycle to electrical splitting of water to form Hydrogen. As it does not use electricity, it can be far more efficient for a thermal plant, as it does not lose out on entropy grounds. It is:

Temp	***Reaction***		
800°C	$2\ SO_3$	→	$2\ SO_2\ +\ O_2$
450°C	$H_2\ SO_4$		$H_2O\ +\ SO_3$
450°C	$2\ HI$	→	$H_2\ +\ I_2$
120°C	$SO_2\ +\ 2H_2O\ +\ I_2$	→	$2\ HI\ +\ SO_{3\ 2}$



As a collection of 4 reactions it has the net effect of taking water to Oxygen and Hydrogen, but merely requires a heat source at around 800°C. Note that 800°C is hotter than is currently used in steam turbine generating plants, but is within that which Thermal plants could produce. Furthermore it should be noted that efficiencies rise rapidly as temperatures are increased; the reactions themselves can be carried out at higher temperatures than indicated.

Haber-Bosch Process

This process produces ammonia, used for nitrate fertiliser production worldwide. It is the largest industrial process on the planet, consuming around 2% of total world energy. It is:

Temp	***Reaction***		
450°C	$N_2 + 3 H_2$	→	$2 NH_3$

Again, this process merely requires a reasonably high temperature heat source, atmospheric Nitrogen and a source of Hydrogen. In practice, the heat source is either fossil burning or the waste heat from the sulphuric acid production. Currently Hydrogen is produced by the steam reformation of methane, which emits CO_2. Again temperatures and pressures vary, with the potential to adjust to better fit available sources of heat.

The subsequent conversion of ammonia to nitric acid for fertilisers is the Ostwald Process, a comparatively straightforward process of combustion in Oxygen and adsorption in water.

> ***It is difficult to fully appreciate the importance to humanity of this disarmingly simple chemical equation. Planet earth would be simply incapable of supporting anything like its current human population save for the discovery and mass production of nitrate fertilisers all of which depend on this simple, but energy demanding, chemical reaction.***

Cement Production

Cement production consumes around 2% of world energy, but produces around 5% of its CO_2.

Temp	***Reaction***		
800°C	$CaCO_3$	→	$CaO + CO_2$

This is a key high-energy reaction, and produces CO_2 as a waste product. In later sections, it will be seen that scavenging this CO_2 for fuel production is both possible and useful.

Iron Production

This process consumes close to 2% of UK energy, and is currently considered an unavoidable CO_2 source

Temp	***Reaction***		
	$2 C + O_2$	→	$2 CO$
	$3 CO + Fe_2O_3$	→	$2 Fe + 3 CO_2$

Ancillary reactions decompose Limestone as in Cement production, a currently unavoidable source of CO_2. The CO_2 from Iron reduction however is avoidable. The first notable fact is that the reduction takes place with CO, rather than CO_2. However, the thermally drivable reverse water gas shift reaction returns CO_2 to CO using thermally produced Hydrogen. The heat output of the coal combustion can be replaced with an external heat source, leaving:

Temp	***Reaction***		
	$3\,CO + Fe_2O_3$	→	$2\,Fe + 3\,CO_2$
	$CO_2 + H_2$	→	$CO + H_2O$
Net Effect			
	$Fe_2O_3 + 3\,H_2$	→	$2\,Fe + 3\,H_2O$

as the relevant pair of reactions, with the same unavoidable Limestone decomposition to remove acidic impurities. Alternatively, the Bosch reaction can reproduce the Carbon from the output CO_2, although this is less energy efficient.

Synthesis Reactions

These are:

- Water Gas Shift Reaction
- Bosch reaction
- Sabatier reaction
- Fischer-Tropsch Synthesis

These reactions collectively take some combination of Hydrogen and Carbon Dioxide and produce water and other products. By careful control of reaction conditions and catalysts, the nature of these other products can be arbitrarily changed. This is the basis for syn-gas, syn-petrol and coal liquefaction. As a process, it is more difficult to produce molecules with long carbon chains, as carbon dioxide has only a single carbon. Typically, this is achieved by adding other starting molecules, or repeated application of the process.

Aluminium Production

This process consumes almost 2% of UK electricity production, and currently needlessly produces CO_2. Aluminium is extracted from its oxide by high temperature electrolysis in a cryolite solvent. The required heat is supplied by the combustion of a carbon anion. This is done partially to prevent recombination of the produced Oxygen with the Aluminium. Such concerns can again be ameliorated without use of a carbon anode by performing the electrolysis under a carbon monoxide atmosphere. Again the reverse water gas shift reaction regenerates the CO with H_2, and external heating can keep the cell contents molten. As with Iron production, the Bosch reaction could directly produce the required carbon for anodes.

Water Desalination

Whilst desalination is not widespread at the present time, significant agricultural regions are using water from non-renewable aquifers. Particularly notable is the Ogallala aquifer, a fossil water source which supplies 30% of US irrigation water. Similar issues of lack of fresh water exist in the South East of the UK. Clearly, the use of waste heat from power stations for desalination is attractive, and should be integrated into new build coastal power stations, where-ever the use of combined heat and power is limited.

6 Reactor Design Choices

A Hypothetical Optimum Reactor

Evidently, the reactor should be safe. In practice, this means that the reactor should have the following properties:

- Natural stability at a set power level,
  - which can only be actively changed
  - which would naturally decay and thus require active control to prevent a return to idle conditions
- Multiple passive methods to shut down the reactor in the event of breaching normal operating conditions
- Multiple levels of containment in the event of a breach
- Produce little long term waste
- Require no enrichment capability to operate, to prevent proliferation
- Produce a large quantity of power for its size and fuel consumption

Coolants

The choice of coolant in any thermal power station is clearly important as it defines the limits of the operating temperature of the cycle. Water and steam have been used, but above around 600°C steam has problems in its tendency to heavily erode the pipes containing it. The pressure caused by the increase in temperature also makes plant failure destructive, and thermal transfer more difficult, as efficient heat exchangers are not amenable to high-pressure gradients. Any gaseous coolant also has the difficulty of low density, which reduces the amount of power taken per unit volume and thus increases the size of the core.

Proposals have been made to use gaseous coolants, specifically Helium, and replace the standard Rankine Cycle with the Brayton Cycle for potential efficiency gains. This is primarily due to allowing higher inlet temperatures. Whilst this may be useful, the primary coolant for a reactor should be chosen to minimise the reactors size and safety. By these metrics, high pressure gases fail. If needed, the primary coolant can be used to heat a gas as a secondary coolant, but the material circulating in the reactor should be a low pressure liquid. Helium also has problems, in that its production is a byproduct of natural gas extraction, and is thus far less available if fossil use is to be curtailed.

We seek a low pressure at high temperature. The coolant clearly must be mobile i.e. fluid, Liquid coolants have clear advantages over gaseous coolants. Consideration of materials liquid at 600°C to 800°C yields liquid alkali metals and ionic salts as plausible coolants. Since at such temperatures many reactions will happen very rapidly, and considering the possibility for accident to expose a coolant loop to the atmosphere or water, alkali metals are an evidently poor choice as they react exothermically with both water and Oxygen. Considering the metal salts, we again have to consider which salts are preferable. Given that Oxygen is itself reactive, we should use a selection of salts that do not react in oxygen. The only such salts are oxides and fluorides. Since metal oxides are generally not molten at these temperatures, we will consider metal fluoride mixtures as the primary coolant of our hypothetical reactor. In turn issues of neutron moderation and melting points suggest that the coolant be a mixture of Lithium and Beryllium Fluorides.

Breeders and other Fuel Sources

The fundamental difference between breeder reactors and other cycles is the nature of the material that is initially put into the reactor. In a breeder this material is not itself fuel, rather it is a fertile material such as depleted Uranium or natural Thorium. As a result of being exposed to the reactor and its neutrons, this fertile material is converted into a usable nuclear fuel. This fuel is then put into the reactor, or another reactor, and utilised to both produce power and the next batch of fuel. In the Uranium cycle, ^{238}U a waste product of enrichment is exposed to neutrons, which then decays to ^{239}Plutonium. This evidently violates the ideal requirement that no enrichment be required. Furthermore, the production of Plutonium is politically suspect due to the usefulness of this isotope to produce weapons. In addition, the breeding of Plutonium in this manner requires leaving many high-energy neutrons in the reactor, which has twin effects of making both containment and safety harder, and also producing larger quantities of long term waste.

The Thorium cycle, on the other hand, takes natural ^{232}Thorium and exposes it to neutrons. It becomes ^{233}Th, and then decays twice to ^{233}Uranium. This is a fissile isotope, and is used as fuel. Whilst ^{233}U has been theoretically proposed for weapons, it has never been practically used (since the gamma emissions from the decay of ^{232}U and ^{228}Th contaminants would interfere with the electronics of weapons systems). It is thus easier for states to either breed Plutonium or enrich Uranium if they seek weapons. Furthermore, the ^{233}U from this cycle normally contains impurities from ^{230}Th, which prevent the effective use of ^{233}U in weapons without further enrichment. As a result, the Thorium/Uranium breeder cycle does fulfill the requirement that no enrichment be needed to operate the cycle. Thorium also can be bred using moderated thermal neutrons, which are easier to contain and less prone to produce long term waste. It is also notable that Thorium is around 3 times as common as Uranium, and the natural form is almost entirely the useful ^{232}Th.

Since the only naturally occurring usefully fissile isotope is ^{235}Uranium, any non-breeder cycle must utilise this as its fuel. This has immediate issues in that ^{235}U is a mere 0.7% of natural Uranium. Whilst some reactors, notably the CANDUs, can operate without enrichment, they have limited fuel efficiency and produce large quantities of Plutonium as a result of the ^{238}U in their fuel. Hence, these reactors produce large quantities of long term waste and Plutonium, which are both problematic.

Hence overall we see that the preferred cycle is a Thorium-Uranium breeder cycle, as this allows power without enrichment and limiting waste issues, although neutron activation will still cause these wastes to be formed in a traditional design of reactor.

Long Term Waste

Radioactive waste from reactors comes from two sources. The first source, which is unavoidable, is the further decay of isotopes formed by the fission of the fuel. These isotopes are generally of short half-life, and some are used in medicine or industry as tracers or markers. As a collective, their radioactivity drops to 1/1000 of its initial level after 200 years. This is the same metric that is used to determine that waste must be stored for tens or hundreds of thousands of years. Whilst 200 years is a long time, it is well within known capabilities for materials and engineering, and can easily be dry cask stored for this time. Hence, these isotopes are not really a problem.

On the other hand, long term and problematic waste is primarily formed by neutron activation. This is unique to nuclear reactors, as they continually irradiate their fission products with high-energy neutrons from other fissions. These neutrons can interact with the fission products, changing the isotope to a more stable one. As a result, they remain active for far longer, in turn meaning that the waste is radioactive for thousands of years. A secondary source of long term waste is the irradiation of heavy nuclei without causing fission to form other heavy actinides. The two primary routes are the intermediate forms in breeder cycles, ^{239}Neptunium and ^{233}Protactinium, although ^{233}Pa is of less concern as an intermediate on its route to long half-life waste is ^{235}U, a fissile isotope.

Clearly if this could be avoided, the primary rational objection to nuclear power would be averted. This would require that any given piece of fuel be only in the reactor for a *short period*, to ensure that the fission products are not further irradiated, and thus fulfill the requirement of little waste.

Contrarily, fuel efficiency demands that all of the fissile materials undergo fission, which requires that the fuel spend an *extended period* of time inside the reactor core.

Continual or Batch Reprocessing

This problem is averted with reprocessing. In this, fuel is separated from the accrued waste and other products, and repackaged in whatever form is needed for another reactor. There are two types, continual and batch.

In the latter, used fuel is stockpiled and then reprocessed. This generally forces large stockpiles or the fuel staying in the reactor for a long period. Since the former solution leads to weaponisation fears, the latter is used. This means that the fuel for reprocessing is used heavily without the fission products being removed, so the fuel is very radioactive and large quantities of long-term waste are produced. This worsens the situation, as this in turn forces the reprocessing facility to keep the fuel sealed for long periods. This promotes batch processing, as then a facility can be more efficiently used.

Continual reprocessing reprocesses the fuel as it is extracted from the reactor. By reducing the time between removal of fuel and its reintroduction to a reactor, the time between reprocessing steps can be reduced without overwhelming capacity. As a result, the fuel to be reprocessed is much cleaner and safer to handle, which in turn allows faster processing and much lower long term waste production.

Fuel State

Given that the demands of low long-term waste production must be met, it seems that fuel must regularly be removed from the reactor. Given that the reactor is also operating at high temperature, there is the additional demand that the fuel be stable at these temperatures. As a result, using a solid state of fuel is problematic. Removal would mean violating normal operating conditions, and solid fuel will evidently trap gaseous products such as ^{135}Xenon (^{135}Xe was one of the primary causes of the accident at Chernobyl). Use of solid fuel at these temperatures is also made difficult by the temperature, which will melt most uranium salts.

On the other hand, a liquid fuel is easier to handle. Continual removal can be achieved with a simple pump, whilst gaseous products bubble out. Again, issues of safety demand stable salts. Fluorides are preferable since the very heavy actinides such as Uranium have a gaseous hexafluoride state. Consequently, removal of the fuel from the waste can be achieved by bubbling fluorine through the reactor. Most fission products do not have this state, and so will not be removed by this process. Therefore, reprocessing the fuel becomes a comparatively trivial step, which can be performed cheaply on site and with great speed. As a result, the levels of long term waste can be reduced to near zero and the radiological state of the fuel kept very clean.

Intermediate Extraction

Given that the secondary source of long half-life isotopes is by neutron interaction with the intermediate isotope in the breeder decay, it would seem that removing this from the reactor in a similar fashion to the fission products would be beneficial to long term waste issues. For this, either costly processing of the blanket is needed, or some method for easy extraction must be devised. In the case of ^{239}Neptunium, there is a problem in that Neptunium is very similar chemically to the other actinides, and thus cannot easily be extracted. If no such extraction is done then the salt mixture must be fractionally distilled or metals dissolved in acids to remove the Plutonium.

Protactinium, however, is unusual in that its chloride sublimes at around 400℃. Hence having the blanket salt, which is cooler and less irradiated, be a mixture of chlorides has some merit. In this case, intermediate extraction is very easy. This does mean that, if the reactor was accidentally broken open, it would react with atmospheric Oxygen slowly, but without significant heat generation and thus it would be manageable. If intermediate extraction is not done, then the hexafluoride trick can be used to remove the Uranium, and thus the blanket would be a fluoride mixture to breed more fuel.

Fuel and Coolant

A comparison of the fuel mixture and the posited coolant is now informative. Both are postulated to be fluoride salt mixtures, with both being circulated, one to cool/extract heat and one for reprocessing. Given that Uranium or Plutonium Fluoride as pure salts have high melting points, they would have to be mixed with some other fluoride salt. At this stage, it would seem reasonable to state that both fluids are actually the same, so that the fuel itself is used to cool the reactor. This reduces the reactor to a moderating block, to accelerate fission and thus make the fuel critical, and a blanket of either chlorides or fluorides.

Decommissioning

The decommissioning of such a reactor would clearly depend on the exact nature of the reactor. If it were using thermal neutrons in a Thorium cycle, then it is at least plausible that the blanket mixture would absorb the remaining neutrons, and thus limit the radiative damage to the reactor block. In a reactor utilising Uranium and thus fast neutrons, then radiation will be more widely spread. Clearly continual reprocessing would reduce the long term dosing of the reactor block. Given suitable containment, the majority of the facility would be kept nuclear clean, and thus the tendency for massive decommissioning costs would fall. Certainly comparisons with current reactors are somewhat unfair, as the majority of reactors are once-through ^{235}U burners, and these have no place to dump excess neutrons except the building, whereas, by design, a breeder puts its excess neutrons into making more fuel. Given that on average ^{233}U fission produces fewer neutrons than ^{235}U or ^{239}Pu fission, the Thorium-Uranium cycle again will produce less secondary radioactivity and thus dramatically cheapen decommissioning work.

Passive Safety

Clearly any reactor employing a molten salt for coolant is almost immediately immune to coolant boiling leading to a physical explosion, as occurred at Chernobyl. These salts do not boil until raised to between 1200℃ and 1600℃, depending on the precise salt, by which time passive controls can easily shut down the reactor. A simple plug, for example, preferably requiring active cooling to prevent melting even under normal conditions, can remove all of the fuel from the reactor if required. Other passive systems can close off fuel flow unless electromagnets are kept on, or release high-pressure gas to forcibly remove the fuel from the reactor if needed.

Other useful features of passive safety again stem from the combination of fuel and coolant as a liquid. If the 'coolant' begins to boil, in spite of other controls, the mass of fuel in the reactor falls, so power output falls. Similarly if core temperature rises, then thermal expansion of the fuel reduces the fuel mass, and so power output falls. Hence these reactors exhibit negative void and temperature coefficients, and thus have a stable natural output level. This level can easily be altered by control rods, preferably being held up by electromagnets against gravity. Hence, again passive controls can ensure that current is cut and the rods drop, again completely shutting down the reactor.

Hence such a reactor supports multiple methods to passively shut the reactor down; many of these are based on the inherent flexibility of the fuel being a liquid and thus mobile.

Clearly also multiple containment methods can be used. Given that the core moderation is needed to make the fuel critical, the fuel itself can be stored in an external tank. The high power density of such a liquid cooled core should allow for smaller cores, which can be buried to reduce attack profile and radiation escape. Use of Boron and concrete between reactor and primary heat exchanger, and between reactor and re-processor, along with external cases, can prevent radiation leakage during normal operations. Furthermore, the inability of the reactor to explode either physically or chemically, or to undergo meltdown, should prevent these barriers from being breached even under emergency situations.

Active Safety

Clearly, the suggested passive safeties can be independently, actively, activated. Movement of control rods, shutting off some fuel channels and flow restriction can all be applied, although in no case should active control be able to override the passives. Hence the naturally stable power output can be adjusted, and the reactor can generate this new level of output, without undue concern for the immediate safety of the plant. Even under extreme scenarios, such as outside agencies deliberately damaging the reactor under normal conditions so as to bypass some of the passive safety measures (Aircraft crash), active control can remove the fuel from the reactor in its entirety, thus effectively preventing accidents or deliberate attacks being viable, unless such an attack removed all active control capability without altering reactor conditions or secondary control. Even in this scenario, the requirement of active 'do not shut down' commands to all passive safeties to prevent shutdown effectively means that the reactor will shut itself down even under ridiculous scenarios.

Conclusion

Overall, we thus see that the closest that we can currently achieve to the stated ideal reactor is a Molten Salt Thermal Reactor. By using a molten fluoride salt mixture as both fuel and coolant, we can ensure negative void and temperature coefficients, whilst adding passive safety options in fuel removal. We also gain later efficiencies as we are producing very high-grade heat, as the salt mixture can be strongly heated in the reactor. By using a Thorium-Uranium breeder cycle, we can remove enrichment and proliferation options from the reactor, whilst use of in-situ continuous reprocessing essentially eliminates the long term waste problem and further hinders proliferation, as any removal of fissiles would tie directly into the stock and power production of the reactor. The only radioactive materials that leave the site should be the short half-life fission products, whose removal in dry casks for long-term storage can be carefully monitored to prevent diversion into a dirty or poor efficiency nuclear program. Using Thorium for breeding also allows heavy in core moderation to a thermal spectrum of neutrons, with the immediate advantage of comparatively trivial external shielding with water or concrete.

7 Overview of Transport Fuels

Candidate Fuels

The main candidate fuels are:

Long chain Alkanes	(Petrol, diesel)
Short chain Alkanes	(Propane, butane)
Hydrogen	
Short chain Alcohols	(Methanol, Ethanol)
Short chain Ethers	(DME)

CO_2 Emissions

The emissions of all these fuels over their life-cycles are dependent on their production method.
If they are derived from recently grown crop they may be carbon neutral.
If derived from atmospheric CO_2 and clean Hydrogen via gas shift reactions and then Fischer-Tropsch or other thermo-chemical synthesis then again they are clean.

On the other hand, if the currently cheapest methods are used, such as the steam reformation of methane to produce Hydrogen, then they may actually be dirtier than their starting constituents. Current sources of long-chain alkanes are all CO_2 dirty, being fossil derived. Similarly the short-chain alkanes and Hydrogen, derived from natural gas and by cracking of other fossils or steam reformation respectively, are not CO_2 neutral.

Alcohols can be clean, although this is reliant on the CO_2 neutrality of the agriculture that produced them. (i.e. we need to consider the energy and CO_2 emissions used in the production of any fertilisers used to grow the crops that are used for bio-fuel).

Short ethers are not currently produced, as there is little current demand for them as fuels. They are chemically similar to alcohols, with DME being similar to ethanol, with a structural formula CH_3-O-CH_3. These, along with short alcohols and short alkanes, can be produced from Hydrogen by gas shift reactions.

Other Emissions

Whilst the level of other emissions such as NOx and soot depends on engine design, in general any fuel without a C-C bond does not produce soot (DME, methanol, methane, Hydrogen). Given that we are considering fuels for transport, it is clear that, if possible, a particulate free fuel is to be desired. Carbon monoxide emissions are inherent to any fuel containing Carbon, and NOx to any combustion engine, but both are removed by catalytic converters.

Storage and Safety

Long chain alkanes and short alcohols can be stored at room temperature and pressure. DME can be stored at room temperature and slight pressure (5atm), whilst short alkanes require higher pressures (10-20atm). Hydrogen is very difficult to store, being impossible to liquefy by pressure and thus requiring cryogenic storage and pressure. Neither Hydrogen nor short alkanes are easy in transport. In the event of accident, Hydrogen and short Alkanes will physically explode when their container is ruptured. Hydrogen burning is almost invisible to the naked eye, with only a slight blue tinge. Hydrogen tanks also inevitably leak due to the small size of the molecules. In terms of longevity in the environment, all alkanes remain in the environment for long periods, with methane having a half-life of 7 years. Hydrogen is not persistent, whilst alcohols rain out and are destroyed in the ecosystem. DME vapourises quickly, and has a half-life in the atmosphere of only 5 days.

Mass Production

The mass production of any of the short chain fuels can be achieved with no CO_2 production using Gas Shift reactions and Hydrogen production without the need to use any fossil fuels. This in turn requires either mass electrolysis or a thermo-chemical process for the production of Hydrogen. The former requires greater generation and thus likely larger CO_2 emissions than thermo-chemistry due to entropy inefficiencies.

Mass production via photosynthesis and biological processing has the attendant problems of arable land limits. Considered from the perspective of long-term demand for plastics, which will require use of gas-shift regardless if fossils are to be avoided, the motivation for a non thermo-chemical source of fuel is weak.

Upgrade Path

Long term issues exist in many cases with chicken and egg upgrade issues. In the case of Hydrogen, the need for large scale specialised infrastructure for fuelling prevents suitable cars from being built, whilst a lack of cars prevents the infrastructure from being built. Alcohols and Ethers can have similar viscosity and flash points to the long chain alkanes, thus making the alteration to engines comparatively small (typically cam timing and injector alterations).

DME in particular is a straightforward replacement for diesel, with a cetane number of 55, at the top end of effective performance for current diesel engines. When combined with water, DME forms methanol, an efficient petrol substitute, with an octane number of 113 and comparable power for a given volume of combustion as petrol.

Short Alkanes and Hydrogen generally require larger scale changes, due to their high vapour pressures and thus drop in temperature when decompressed. In terms of fuelling, DME, Alcohols and Long Alkanes are probably still user fillable, whilst short Alkanes and Hydrogen would require non self-service. Alcohols have a known mix based path to reduce petrol use, and DME is likely to be amenable to a similar approach.

In the case of aviation kerosene, the need for high energy density in a low-pressure liquid effectively mandates the use of aviation fuel. Hence, attempts to reduce total CO_2 output of aviation will have to focus on Fisher-Tropsch synthesis of long-chain alkanes, in spite of the implicit [in-]efficiency and cost issues.

8 Combined Hydrogen and Power

Noting the established use of heat sources for purposes other than electricity production, we clearly wish to use what heat we can for the heating of materials, specifically in industrial processes. If we consider that at present transport accounts for around 20% of global energy consumption, and a greater percentage in the West, it is clear that fuel production will be an important large-scale process. If we further consider the limitations on Bio-fuels, then it becomes clear that thermo-chemical production will be vital. Given that these fuels inevitably use Hydrogen for their production, the ability to produce Hydrogen around an electricity generating cycle is clearly useful. Given that standard turbo-machinery for steam operates beneath 565˚C, there is considerable synergy with the Sulphur-Iodine process as follows:

Temp	***Reaction***		
800˚C	$2\ SO_3$	→	$2\ SO_2 + O_2$

Specialised high temperature turbo-machinery operating with a non-water fluid, such as helium, nitrogen or mercury, cools a secondary coolant loop from around 800 ºC to a lower temperature around, but preferably above, 450 ºC. Alternatively we could directly heat water from 120ºC to 565ºC for a steam turbine; this is less efficient but easier.

Temp	***Reaction***		
450˚C	$2\ HI$	→	$H_2 + I_2$
450˚C	$H_2\ SO_4$	→	$H_2O + SO_3$

Standard steam turbo-machinery drops temperature from around 450ºC to below 120ºC. The exothermic bunsen reaction can be used to reheat steam at this point.

Temp	***Reaction***		
120˚C	$SO_2 + H_2O + I_2$	→	$2\ HI + SO_3$

Low Pressure Turbines drop temperature to around 40˚C
Other proposed systems can now drop from 40˚C to near room temperature; possibly using air turbines, desalination or combined heat and power.

As a result, a single high temperature heat source drives both the Sulphur-Iodine cycle and utilises the gaps between the reaction temperatures to produce electricity. Alternatives could fill these gaps with other processes, such as the 450-600˚C Haber-Bosch reaction or clinker heating for cement.

In the case of "Combined Hydrogen and Power", the drops in the three reaction stages can be lowered, thus diverting energy to electricity production, at the cost of reducing the rate of Hydrogen production. As part of a larger grid, this allows Hydrogen production to act as a short term storage system, as thermal plants can avoid the difficult long-term throttling of their heat source, whilst altering electricity output. In principle, this allows previously considered backbone generation to respond to demand comparably or faster than gas turbines. This allows far greater levels of renewable usage in the grid mix, as the responsiveness of the rest of the grid to varying renewable output is increased.

Whilst this is similar to other energy storage mechanisms, fuels have the twin advantages of being far more energy dense (5.5 MWh/ton for methanol, 7.7MWh/ton for DME) than other proposed stores, and secondly being continually used. The UK strategic stockpile, of 3 months petrol for the country, is far larger than required for evening out short term variability in power requirements.

9 Industrial Use

For wide-scale integration of new power sources into industry, the energy must be provided in a manner that industry requires. In many cases, this is not electricity. Whilst electricity is a useful form of energy for domestic consumption, as its usage does not produce inherent waste heat, industrial processes normally merely require temperature or pressure, both forms of work are easily provided by heat engines. As a result, in terms of total energy production it is more efficient to use less pure forms of energy. As a result, most industry consumes heat from fossil fuels, although for certain electrolyses and very high temperature processes electricity is used directly. For the majority of industry, however, a simple heat source suffices. As a result, the production of a compact and efficient high temperature heat source is extremely useful. In modern industrial chemistry, many processes are driven by the waste heat of sulphuric acid production. The thermal energy from a MSTR is of a comparable temperature, and can more easily be increased if needed.

In essence, as soon as such power sources are easy to install and operate, industry will use them. If incentives are given to make the change, then usage will become widespread very rapidly. Furthermore, industry is best placed for carbon capture. Processes such as iron or cement production inherently produce CO_2, and the capture of this and thermo-chemical conversion to fuel is well within their existing realm of expertise. When these wastes can be turned into saleable product, industry will happily do so.

10 Sequestration

For the purposes of ensuring net CO_2 output over the lifetime is zero, it may be necessary to directly extract CO_2 from the atmosphere and sequester it in some fashion. Current proposals feature direct storage of CO_2 as a pressurised gas or a liquid by placing it in exhausted gas beds or under the ocean. Placement in exhausted gas beds is comparatively trivial in energy terms, but is limited in total sequestration, since oil and coal are far more carbon dense by volume than Natural gas and liquified CO_2, which have around the same carbon density.

Underwater pressurised storage of CO_2 is difficult, as liquid CO_2 is less dense than the surrounding water and requires significant pressure to maintain liquidity. A 90% formic acid solution or some other chemical can be chosen to be denser than water in its liquid form at 4°C, and condense at comparatively low pressure. As a result, ocean bottom storage becomes comparatively trivial, as it merely requires some form of bagging to contain it, with pressure keeping it liquid. As these chemicals do not require much pressure to liquify, the energy cost of sequestration is lowered. Even so, the energy cost of the chemical alterations will exceed the cost of compressing CO_2, so ocean floor sequestration is more costly than gas-bed storage.

The density of these chemicals ensures long term stability on the ocean floor. Even if sequestration is not utilised, carbon can be effectively stored as fuel in ocean floor sites over years or decades as strategic reserves, as the initial carbon source was atmospheric CO_2. If the cost of buying the carbon credits to burn fuel exceeds the cost of producing and sequestering that fuel, then long-term sequestration becomes profitable and will be done by the market.

CO_2 compression into a gas bed remains the cheapest option, followed by storage as some denser than water chemical at high pressure on the ocean floor, as the cost of moving it there is negligible in energy terms.

11 Geopolitics

The resultant large-scale geopolitics clearly vary from solution to solution. While the fundamental main energy source remains long chain mined alkanes, the middle-east OPEC countries will retain political power. Under proposed wind or PV powered systems, political power will not be with the fundamental source of power, being natural, but the manufacturers of the systems. Under a wind system, these will be countries with large quantities of cheap heavy industry; China and other low cost manufacturers are the likely winners. For solar PV, there is the additional complication of requiring a large electronics industry. Again China could take the lead role in manufacturing, but their delicate nature for transport and the existence of domestic expertise makes it possible that Japan, Europe or the US will take the lead.

Under a Solar thermal or solar PV system, the placement of the systems is also important. The need for large empty areas of unpopulated land with high levels of isolation immediately point to existing deserts, in Africa, the middle East, the high deserts of Tibet, and either Mexico or the North American deserts. Unfortunately, given that demand in most countries is not singly peaked at midday, supply would ideally be derived from areas 6 to 7 hours to the west of demand, so that the evening peak in demand is met with someone else's peak production. Hence, Europe would have to be supplied from the US East Coast, not renowned for its deserts. The US East Coast would draw from the West Coast, with reasonable numbers of deserts. The West Coast has no obvious source, whilst Asia could derive energy from African deserts and the Middle East.

Under a Thorium or Uranium nuclear system, fuel is important over the long term, but irrelevant in the short term. Current reserves of Thorium are primarily in the US, Australia and India, although large quantities exist across the planet. Since large price rises in Thorium are almost immaterial to generation cost, if other minerals are a reasonable guide then a small increase in long run price will rapidly increase supply. Uranium is currently mined largely from the Canada, Australia, Kazakhstan and Niger.

12 Conclusion

Considering the proposed solutions, we see that they all have their problems. Traditional renewables and bio-fuel for power and fuel suffer from practical issues on a national grid when scaled, whilst the energy output is marginal in these systems. Replacing Bio-fuels with Hydrogen has consequences for efficiency over the cycle and has other practical problems. An alternative fuel can be used instead of Hydrogen, but the issues of reliability of energy supply remains. The current grid mix has excessive Carbon output. The proposed CHyP system, especially if other low temperature cycles are added, allows greater levels of renewables in the grid, but requires a high temperature heat source. MSTR's have this property, but are not traditionally considered to be green as they are nuclear. However since the objective is a practical system some degree of nuclear must be adopted. Hence the proposed solution is to use CHyP MSTR's for the majority of generation. If investing in renewables allows emissions to be reduced faster, then so be it, but the long-term expectation is that they will be competed out of the market due to their inability to react to market demand. The waste from these MSTR's has already been established to be far less problematic than that of current reactors, and the decommissioning cost lowered by the higher achievable power densities. The proposed solution has the property that it allows a continuation of apparently business-as-usual usage by consumers and industry of energy, whilst cutting emissions to very low levels. Furthermore, it can be introduced slowly, thus lowering the cost of the changes. It does however, require a shift in attitude from nuclear power to nuclear heat, and a shift in regulatory positions to legalise routine on-site reprocessing of the fuel and wider usage of reactors in industry