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Engineering the early demise of fossil fuels

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Abstract: Climate change is now scientific fact, and it is equally firmly established that it is of anthropogenic origins, mainly attributed to the burning of fossil fuels. If future generations are to inherit a living, and livable planet, which is self-evidently their right, the current inhabitants have no alternative but to dispense with fossil fuels as a source of power. It is demonstrated here that technically this can clearly be secured before 2050 by transitioning to renewable sources of energy, backed up by 'clean' nuclear power. However, effective deployment of these geographically widely dispersed power sources will require power sharing among groups of nations and grid interconnections on a continent spanning basis. It is suggested that effective progress towards the realization of such distributed systems is unlikely to be achieved without cooperative planning and implementation across many nations. An example of this is beginning to emerge in Europe.

Keywords: Climate Change, Population, Renewables, Nuclear Fission, Hydrogen

1. Introduction

By 2050, reliable projections based on world wide population statistics, suggest that there will be at least 9 billion people on the planet, with the number perhaps climbing to 10 billion before it levels off late in the current century. These are huge numbers. Filled to the brim, two common household baths could just about accommodate 10 billion grains of common granulated sugar. As I said the numbers are really quite staggering. While this article largely addresses the engineering issues relating to weaning civilization off its addiction to fossil fuels, it is nevertheless important that readers are fully aware of the population issue, since these almost unimaginable numbers, seeking sustenance from our finite planet, will inevitably influence the decisions and actions of governments, at the world level, as they haltingly attempt to respond to the most difficult problem of our times, namely anthropogenic global warming. Coordinated action at the world level is essential if we are to be successful in 'turning down the greenhouse thermostat'. But is it feasible to abandon fossil fuels and rely entirely on 'clean' sources of energy?

2. Atmospheric Symptoms of Fossil-Fuel Addiction

If one plots population magnitude over a 2000 year timescale, the numbers are observed to have been relatively stable, at less than one billion, throughout this period then in the last 200 years they 'take off'. The shape of the population curve versus time is not unlike a hockey stick, with its shaft horizontal and its blade pointing upwards at the right hand end (fig. 1). The concentration (versus time) of carbon dioxide in the atmosphere displays a similar shape, and it is not unreasonable to aver, and most rational people now do so, that the CO_2 trend must be related to human numbers and human activities. The 'hockey stick' shape is also exhibited by graphs of average global temperature versus time, although the degree of correlation between planetary warming and population/atmospheric carbon still remains, for some, an open question. The debate largely revolves around the way in which temperature is collected from proxy sources like tree ring widths and how this kind of data is converted into average temperature. However, as new research results appear and as the volume of supportive measurements grows, the relationship between human induced greenhouse gases and warming is becoming difficult to refute. The vast majority of serious scientists now accept the link.

At this present moment in time, the industrial world's largely neo-liberal power structures seem determined to continue using fossil fuels until reserves are exhausted. This however would be foolish in the extreme, since there is still more than 10,000 Gigatons of carbon [1, 2] underground in the form of natural gas, coal and oil. If left untouched, it is safely sequestered. On the other hand, if it is all incinerated to provide energy, the carbon dioxide in the atmosphere will rise to four times above pre-industrial levels. The best climate simulations suggest that this would result in a disastrous 6.3^0C average rise in global temperature [3]. Even a 2^0C rise in average temperature due to greenhouse gases is considered to be dangerous on the basis of reliable scientific evidence, a particular example being permafrost destabilisation. Two degrees could trigger (a 6.3^0C rise most certainly will) unstoppable non-linear processes which may plunge the climate towards a hot epoch – possibly too hot for many mammals including mankind.

Perhaps we could burn the remaining fossil fuels safely by employing carbon capture and storage (CCS)? Unfortunately, at the global level, carbon capture techniques are of doubtful benefit [4]. While it may be possible to store some liquefied carbon dioxide in worked-out coal mines, depleted oil and gas wells and perhaps natural caverns, most of the greenhouse gases produced by burning the remaining reserves of fossil fuels will have to be released into the atmosphere. This is because coal is almost pure carbon, while carbon dioxide which is one part carbon and two parts oxygen occupies a volume close to three times greater than the original coal. Consequently, there is not enough suitable underground storage capacity globally to accommodate much more than about a third of the waste CO_2, from burning coal. This observation is based on the presumption that the well documented problems of simply pumping CO_2 into the deep ocean as an effluent, or of sequestering it by chemical methods, will remain unsolved in the foreseeable future. It should also be added that so called 'clean' coal, as the spin merchants like to describe it, is by no means clean. A coal powered station incorporating CCS, is no better in environmental terms than a conventional gas powered station, which can hardly be described as 'green'. Of course, the carbon capture hype ignores the fact that all of the harmful CO_2 generated by transport, which is not insignificant, cannot be captured.

3. Transition to Renewables

The only safe route forward for the planet is for mankind to abandon fossil fuels as a source of energy in a timescale measured in years, rather than decades. So what routes are technically possible that could achieve a rapid transition to other energy sources without, at the global level, instigating a deep economic recession triggered by severe energy shortages? On a business-as-usual basis, it is not difficult to project, from the literature [5, 6], the likely global energy demand out to about 2050. Typical worst-case and best-case scenarios are depicted in fig. 2. On the other hand predicting possible growth scenarios for the supply of power from renewable sources over the same time interval is much more uncertain [7]. Some progress can be made, firstly by estimating, on the basis of fundamental physics, the degree to which large-scale renewable energy sources (wind, wave, tidal, hydro, solar, and geothermal) can feasibly be exploited while respecting other earthly activities, and secondly by pursuing efficiency calculations on the collected power as it is subsequently processed through various stages of electricity production. Predictable power losses occur in turbines, generators, up-conversion transformers, transmission over long distances on the grid, down-conversion transformers and distribution to consumers, so it is possible to ascertain [7] that, despite the 'hype', the power available to users globally is by no means limitless. 'Firm' estimates for ultimate electrical power levels, which can *realistically* be extracted from accessible renewable sources, viewed from the perspective of power station level exploitation, are summarised in table 1, (see the column labelled (2050+)). 14TW by 2050 is deemed to be possible (see fig. 2), which is insufficient to meet even the 'best-case' energy demand by 2050. The power estimates listed in the table are of an accuracy, which an engineer would describe as being of 'ball-park' reliability, since they are based mainly on engineering evaluations of the science and technology, but with some geographical and geological guesstimates thrown in.

Biofuel is considered by some to be capable of making an important contribution to the renewables 'revolution' but in a world with population predicted to rise to 11-12 billion by 2100 it is very unlikely that governments around the world could justify more than 5% of arable land to bio-fuels. Official estimates provide the statistic that 6% of renewables from bio-fuel would require about 20% arable land area. Bio-fuels from algae could make a contribution but this is also likely to be limited. Apart from the fact that biomass yields are much lower than claimed (in reality not much higher than regular agriculture) and that costs are very high (at least 10, but often over 100 times more expensive biomass production costs, especially in closed systems), as yet, algae simply doesn't deliver net energy: the energy content of the fuel is lower than all fossil fuel inputs needed for cultivating, feeding, harvesting and processing, and building the infrastructure. At present the evidence is that these first generation biofuels tend to produce more GHG-emissions than fossil fuels. In the fight against global warming it is unlikely that bio-fuels will contribute more than about 2% to the renewables total (i.e. ~0.4TW – see table 1).

It is possible that up to another ~2TW could be garnered by small scale wind and roof-top solar activities around the globe, but these have not been factored into the estimates since the numbers are rather too unpredictable.

To fill the energy gap humanity will need an infusion of 'clean' nuclear power. Recent developments in this sector indicate that Integral Fast Reactors can provide 'cleanly' and 'safely', essentially perpetual nuclear power [8] and consequently it would be prudent to include this resource in a future energy mix. Functionally, a nuclear power station largely replicates a coal fired power station except that the thermal energy is generated in a nuclear core rather than by combusting gas, oil or coal. Consequently, the currently well publicised statistic that China is building one coal power station per week, gives support for the cautious proposal that the world community could, from a purely technological perspective, build two IFR's of 2GW capacity every week from 2020 to 2050 [8]. This contributes 0.2TW/year to the global 'clean' power supply portfolio, as suggested in fig. 2. In combination with the development of renewable power over this period, fig. 2 suggests that fossil-fuels could be phased out comfortably by 2045.

Table 1. *Feasible installed renewable power at global level: by 2050.*

Resources [assuming exploitation takes place at the power station level]	**Available power at the point of consumption (TW) (2050+)**	**Comment**
Hydro	~2.0	Unlikely to be much more than 2020 capacity
Wind	7.5	Covering, in area, a land and continental shelf equivalent to Mexico
Wave	0.022	Located in known and easily accessible off-shore sites
Tidal	0.2	Located in the few promising estuaries and straits which have been identified
Solar	4.5	In suitable desert sites occupying an area equivalent to that of the Iberian Peninsula
Geothermal	0.14	From known active and optimum geological sites
Nuclear	5.2	Assuming clean IFR's can be built at rate of two/week from 2020
Biofuel	0.4	Limited by fact that use of arable land for biofuels will be controversial
Total	~20.0	as population rise above 10 billion
Fraction of (projected demand)	66% (of ~30TW))	With aggressive efficiency drives this can be 100%

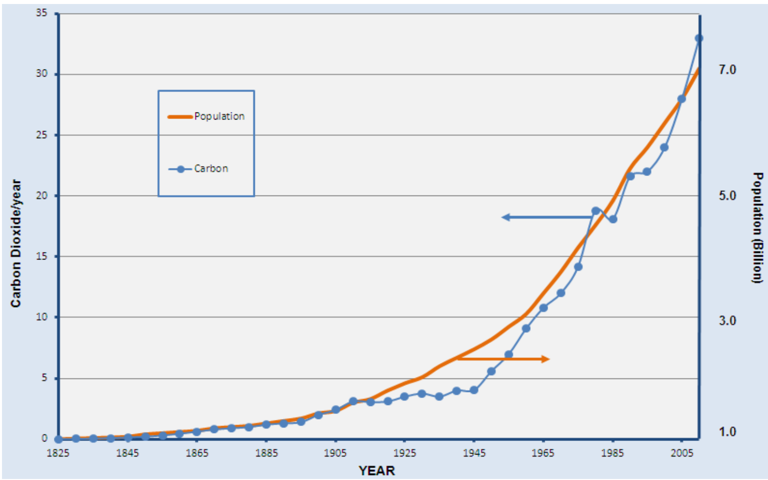


Fig 1. *Growth in population since 1825 compared to rise in carbon emissions (gigatons CO_2/year)*

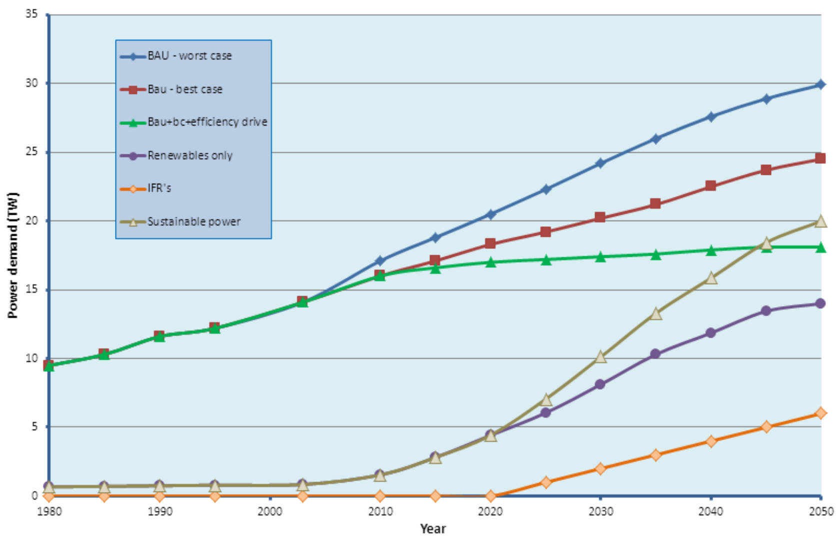


Fig 2. *Global power demand extrapolations to 2050 and feasible power generation growth based on sustainability*

Consequently, from a purely engineering perspective the sensible way forward for mankind is a whole scale and rapid adoption of renewables, backed by an aggressive efficiency drive and supported by a modest IFR build rate. The switch to renewable power for the bulk of our energy needs will have to incorporate a wide range of technologies as we have seen. But the exercise will also need to be coordinated on a continental scale, and will probably need to employ superconducting DC grid connections where large distances are involved. It is interesting to note that a superconducting 600m long transmission line connection recently installed and demonstrated by the Long Island Power Authority in the USA was cooled by forcing liquid nitrogen through an annular space in the coaxial cable. The voltage was 138kV and 2000A flowed in the cable. This represents the same power carrying capacity of a conventional 345kV overhead line, but with virtually no transmission loss. New technologies such as this will evolve from an aggressive strategy of efficiency improvement in the supply of electrical power, and in how it is used [9] (see fig. 2 green curve). For example, in the not-too-distant future, modern materials offering room temperature superconductivity may dispense with power hungry cryogenic requirements while greatly reducing the severe ohmic losses incurred by the electrical supply industry in currently chronically inefficient electrical devices and systems. An efficiency strategy is unavoidable if a supply and demand balance by 2050 is to be secured.

A feature of renewable power sources such as wind, wave and solar, which is raised repeatedly in debates about their capacity to replace fossil fuel powered electricity generators, is intermittency of supply. However, at the global or continental level, the variability of renewables can be addressed much more easily than it can within small nations. In the European sector of the globe, when the wind is not blowing in Scotland it will likely be blowing in Germany! Under the auspices of the European Community, EU states have signed up to an ambitious pan-European energy policy. Several reports have been generated to assess the feasibility of a direct current (DC) super-grid connecting geothermal power stations in central Europe, solar power stations in southern Europe and North Africa, wind farms in Western Europe, wave/tidal systems in Scandinavia and Portugal, and hydroelectric stations in Northern Europe (see fig. 3). This system would be backed up by massive storage facilities based on compressed gas and hot water thermal storage using cathedral sized underground caverns, on massive flywheel farms, on battery storage barns the size of football pitches and on huge super-cooled magnetic storage devices. Prototype examples of all of these technologies already exist. In relation to long distance electricity transmission, undersea power lines from Scotland to the continent of Europe, and across the Mediterranean, are seriously being evaluated at the present time [10, 11].

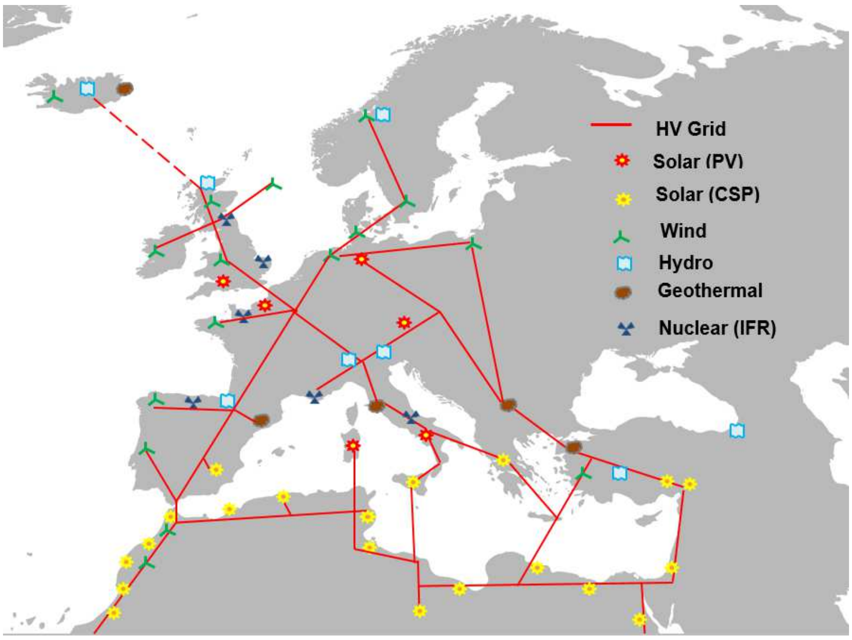
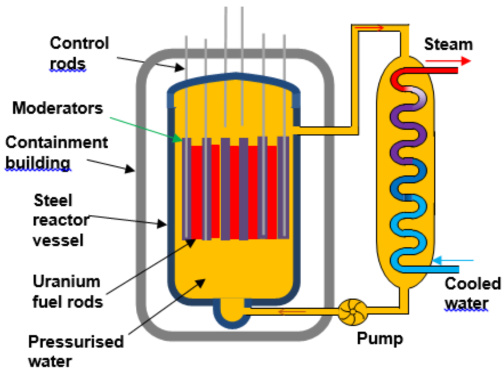


Fig 3. *Rudimentary representation of the postulated European Community renewable energy distribution grid*

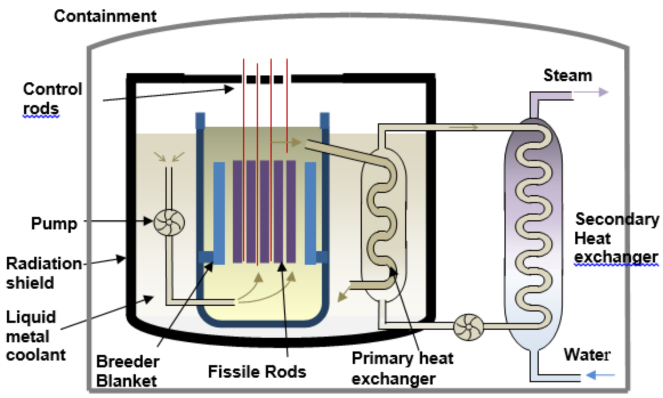
It should be emphasized that almost all of the renewable technologies listed above are relatively conventional. In principle, therefore, sustainable power systems based on these technologies could become available very quickly if implemented by an international community imbued with the drive, determination, and enthusiasm to give succour to the environment. It will entail the release of economic resources on a 2008-bank-crisis scale, and the recruitment and deployment of human resources on the level of a major military campaign, employing large numbers of trained scientists and engineers. But where, at 'short notice', would the scientists, engineers and technicians required to implement the paradigm shift to renewables come from, and how could the required unprecedented expansion of manufacturing capability be achieved? The major components of renewable power stations, such as turbines, gear trains, generators, propeller blades, nacelles, control electronics, management systems, metering, mirrors, etc., are, in engineering terms, not unlike what is currently manufactured in considerable volume by the automobile and aeronautic industries. Consequently, the engineering answer to the above question is not too difficult to enunciate if we accept that the future is sans coal, oil and gas. We must commandeer these industries and shift their manufacturing emphasis away from the building of soon-to-be-redundant fossil-fuel powered vehicles and aircraft, towards providing a publicly owned electrical power supply system based on renewables, and we must use the capabilities of other fossil fuel dependent industries, such as those involved in chemicals and plastics, to develop massive electricity storage systems and materials for a superconducting grid.

4. Contribution from Nuclear Fission

The technology which is most often cited as the successor to fossil fuels, particularly in relation to the generation of electricity, is nuclear power. There are three distinct alternatives. They are nuclear fission light-water reactors (LWR) or pressurized water reactors (PWR) burning processed uranium, integral fast (breeder) fission reactors (IFR's), and fusion reactors. Currently, in most developed economies electric power represents only 10% of the total power consumed. In the post fossil fuel age, however, it seems likely that much nearer to 80-90% of our power will be supplied through the electricity grid, and on current trends the amount will be colossal. By 2050 reliable estimates, from a range of economic forecasters, are that global power consumption will reach 25 Terawatts (25 million megawatts), if 'business as usual' growth patterns are assumed. This means that to totally replace fossil fuels by 2050 with LWR/PWR plants alone, we would need 50,000 nuclear stations of typically 500MW capacity. This is an utterly impossible target. At a very optimistic rate of build of two a week until 2050 we will achieve only 3000 additional nuclear power plants. But what is even more inhibiting, is the fact that at this rate of build and operation, readily accessible reserves of uranium ore run out at about 2040.



(a) Conventional pressurised water reactor



(b) Integral fast reactor

Fig 4. Comparison of (a) the thermal nuclear reactor (LWR/PWR) and (b) the integral ast reactor (IFR)

Nevertheless, nuclear reactors could be part of the renewable energy mix by adopting Integral Fast Reactors (IFR's) which exhibit a quasi-renewable operational mode by making much more efficient use of nuclear elements (uranium or thorium) and nuclear by-products contained in 'spent fuel' [8]. As has become apparent after more than 60 years of commercialisation endeavour, conventional thermonuclear plants are now considered to be too dangerous and too polluting for world-wide roll-out, for a wide variety of reasons the most damning of which is the toxic waste. The risky nature of thermal nuclear reactors is illustrated in fig. 4a. The water coolant has to be pressurized to prevent it turning to steam within the reactor vessel. This means that pressurization failure can lead to overheating in the fuel rods and a 'run-away' reaction, as occurred at Chernobyl in April 1986. Furthermore, the fact that the coolant can transport radioactivity outside of the containment building (see fig. 4a) through a single stage heat exchanger which is usually sited externally, represents a major drawback for the PWR design.

The pollution problem is exacerbated by the inefficiency of the controlled 'slow' neutron reaction employed in thermal reactors. It converts only 5% of the nuclear fuel to useful heat resulting in 'waste' products which are replete with long-lifetime radioactive elements. In addition the presence of plutonium in the waste can be reprocessed to extract weapons grade material. This represents a major political issue which is inhibiting the expansion of nuclear power. The consequence is, perhaps with the exception of France, PWR's are largely being abandoned.

However, the picture is not entirely negative. Liquid metal breeder reactors (IFR's) fuelled by uranium or thorium, despite their reputation of a 'plutonium legacy' are seriously being assessed by Indian scientists to provide energy on the sub-continent. The term 'breeder', which is often applied to integral fast reactors, arises because these reactors essentially operate without moderators (see fig. 4a) to slow down the high velocity neutrons (hence the 'fast' epithet) and this means more efficient fission. For example, in an IFR fuelled from processed uranium, virtually 100% of the fissionable material in the fuel is utilized, while in a PWR it could be as low as 1%. The non-fissionable products from an IFR have short half-lives. Consequently, the spent fuel is potentially relatively easy and safe to store by, for example, vitrification in glass and burying. The problems associated with conventional (PWR) nuclear reactors are largely dispelled by transitioning to this 'fail-safe' IFR technology which adopts unpressurised liquid metal coolant (see fig. 4b) and metal fuel rods. In emergency scenarios which have been simulated in a prototype reactor it has been demonstrated that the metal fuel rods expand if the temperature in the reactor rises, thus reducing, below the critical threshold [8], the density of the fissile material, and automatically suppressing the reaction as a result. Unfortunately, at the present time (2014) IFR's remain well short of commercial operation, so we have to assume that the adoption of this technology to aid the transition to a fossil-fuel free global economy has to be a strategy for the medium term once the renewables based super-grid becomes established.

In the very long term there is, of course, also the elusive promise of plentiful 'clean' energy from the fusion of hydrogen to form helium, as occurs in the sun. Unfortunately, the science is very difficult, and the best estimate for a successful harnessing of this technology is that it is, perhaps, forty or fifty years away – much too distant to be meaningful in the fight to arrest global warming.

5. The Hydrogen Economy

The 'silver bullet' solution for an energy hungry future is often cited to be a hydrogen economy [12] in which thermal energy of fossil-fuel combustion is simply replaced by the thermal energy generated by burning hydrogen in air? There are many modern industrial and other processes which use hydrogen in relatively small amounts, but for these applications the gas is extracted from hydrocarbons. However in a post fossil fuel age this would not be possible and 'clean' hydrogen would have to be separated from water by electrolysis (fig. 5).

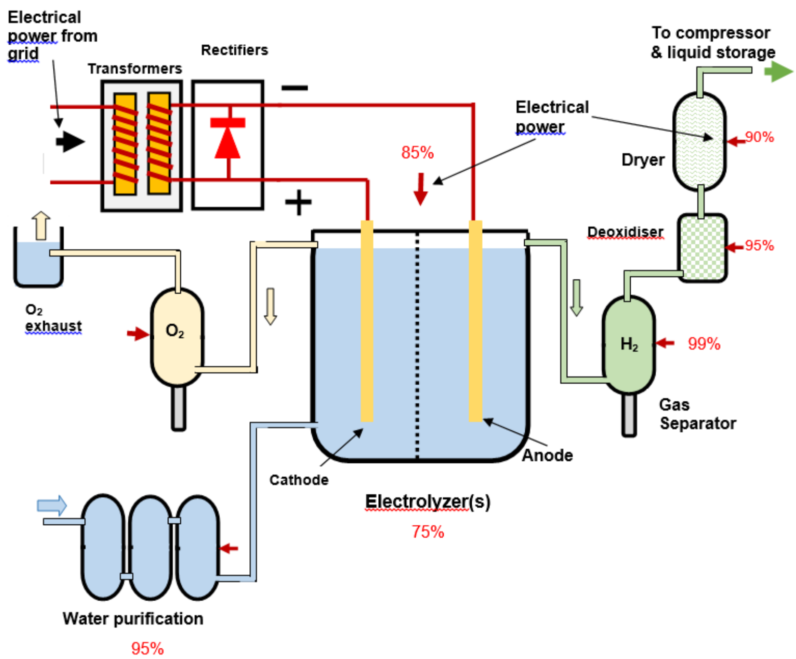


Fig 5. *Schematic of electrolysis plant for hydrogen production highlighting energy efficiencies as a percentage of the supplied power.*

Unfortunately the extraction of hydrogen from water is energy intensive as is shown in fig. 5. It takes about 53 kilowatt-hours to produce 1 kilogram of hydrogen assuming a 75% efficient electrolyser. The whole process, including cryogenically cooling the hydrogen for storage, is less than 50% efficient. Consequently, a 25TW hydrogen based modern global economy, in 2050, will require an electrical power supply industry, relying on renewable sources, delivering an unattainable 50TW, to drive the hydrogen plants. Furthermore, hydrogen has an energy content of 2.3kW-h/litre, and since 25 terawatt for a year equals 220 x 10^{12} kW-h, we can deduce that the modern global economy of 2050 will require 95×10^{12} litres (slightly more than the volume of water in the Caspian Sea) of the gas to be generated yearly. This huge volume of hydrogen would have to be stored, presumably in very frigid liquid form. The power required to do so is not insignificant and just adds to the problems of realising a hydrogen economy. It seems appropriate here to quote from the well known, recently published book 'The Hype about Hydrogen' [12]. In it, the author is motivated to comment that it hardly makes 'much sense to generate electricity from renewable resources, then generate hydrogen from that electricity using an expensive and energy-intensive electrolyser, compress and liquefy it (using more energy) ship the hydrogen over long distances (consuming more energy), and then use that hydrogen to generate electricity again with low temperature fuel cells'. On all the available evidence it is hard to disagree.

6. Power Collection and Distribution

An electrical grid system capable of supplying power from geographically, widely dispersed, sources of renewable power will have to be coordinated by groups of nations possessing some, but generally not all, of the possible alternatives. This power sharing will most likely appear first in Europe. Unlike in the USA, there is a consensus in European Community for addressing climate change, and planning for such a grid (termed the 'eco-grid' for convenience) is actually well advanced [10, 11]. Once the 'eco-grid' is completed for all five continents, Earth will possess an electrical power systems providing power on demand to all nations which are connected to it. Controlling, distributing and monitoring the power will not be particularly difficult with modern sensing, smart monitoring, enabled by satellite communications and sophisticated computer techniques. On the other hand, putting political and economic mechanisms in place to ensure equitable access may be much less simple.

It also has to be said that this worldwide, renewable power, distribution system may be difficult to protect. It will be susceptible to sabotage by incorrigibly warlike humans and to intermittent localised storm damage. On the other hand, this disadvantage is far outweighed by the fact that much of the technology will be largely conventional, well established, and therefore benign. This means that failures will not equate with disasters, as would be the case if vulnerable CCS coal stations, thermal nuclear power stations, and hydrogen power plants were allowed to encircle the globe. The IFR plants which form part of the system are virtually fail-safe [11] and much more secure than conventional reactors. As an applied scientist and engineer with a healthy regard for Edward A. Murphy Jr., who is famous for his observations on the incompatibility of human operators and complex systems, experience tells me that he was very perceptive when he opined that 'if there are two or more ways to do something, and one of those ways can result in catastrophe, then catastrophe is inevitable'. This maxim would make me be very wary of relying on sources of power which are complex, or incorporate untried technology, and are thus prone to catastrophic failure, especially if adopted on a very large scale. So, the 'roll out' of back-up IFR technology will have to be cautious and controlled.

Equally, few rational engineers would entertain extreme geo-engineering schemes designed to mitigate the greenhouse effect, such as seeding space with millions of mirrors to scatter solar radiation into the heavens. A bright (pun intended) idea but terminally disastrous if it goes wrong – as it surely would according to Murphy's law!

7. Politics of Transition

Governments around the globe have the responsibility to satisfy the demands of their large and growing populations, and not surprisingly they do so in a manner which ensures they are elected or stay in power. Mostly they achieve this aim by reassuring their citizens that they will have access to what they all seem to want, namely developed-world standards of living, which generally equates with rampant consumerism in today's global market. This, in turn, entails governments relentlessly pursuing fossil fuel powered economic growth. But with population numbers in the billions it is a policy which is ecologically ruinous. It is also economically disastrous since coal, oil gas, uranium and many other minerals will run out, on current business-as-usual (BAU) trends [13], if they are not already doing so.

The serious error, that governments throughout the industrial world are currently making, is espousing the suspect neo-liberal notion that it is possible to rely on markets to develop a sustainable energy supply system which is of global reach. Some lateral thinking is called for, to evolve a planet-wide, sustainable, energy supply strategy which is independent of the profit motive, and is cooperative and distributive in its primary purpose. After all access to energy, is a fundamental right, or should be, just like water or air. It is instructive to make a cursory examination of the record of power supply utilities both in the USA and the UK, where shareholder owned examples of energy utilities have been allowed to supersede publicly run corporations through privatisation. In the States where 26% of publicly owned utilities still operate in parallel with private alternatives, the former generally provides a better service to customers while offering costs per kWh some 18% below the private operators. In the UK the energy market has been carved up between five major private players. These operate as a cartel imposing excessive charges on customers, to satisfy shareholders, defying all government pressure urging them to do otherwise. The evidence is that extending the neo-liberal energy supply model to sustainable global energy provision would be a major blunder. Actually 'not-for-profit' electrical power supply is by no means a revolutionary idea. It is pursued, very successfully, at the national level in France, through their AREVA national nuclear power agency, which supervises and monitors all aspects of the mainly nuclear power supply industry in that country.

8. Conclusion

In summary, cautious estimates suggest that mankind can transition away from fossil fuel generated power. Globally 14TW of electrical power by 2050 is extractable from renewables with perhaps 6TW from 'clean' nuclear sources. This is not enough to satisfy BAU growth but is more than enough to operate a modern global economy at the level prevalent in 2010 when consumption was about 18TW. With sustained and effective attention to improving the efficiency of the electrical supply industry, to minimizing or eliminating the frivolous use of electricity, and to raising the efficiency of consumer equipment, 20TW can potentially go very much further than current poor practices would allow. Of course, if we could also stabilise the world population at the current level, it would be even easier to secure a sustainable future without fossil fuels, and it need not be so grim or primitive as some would have us believe. Actually, it would be naïve to think that coal will be totally eliminated from use in the 'post fossil fuel age'. But one would assume that it will become a proscribed resource, which is made far too expensive to burn wastefully Hopefully, it will soon be restricted, rather like ozone destroying chlorofluorocarbons (CFC's), to utilization by a limited number of licensed, essential users, capable of guaranteeing that their greenhouse gas emissions are within strictly prescribed limits.

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