# Replacing fossil fuels by renewables:
## It is urgent, technically straightforward and cost effective

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## Abstract
There is a widely believed myth that replacing the use of fossil fuels largely by renewable forms of energy is still critically dependent on the development of appropriate technologies. Accordingly, it is held that decarbonising straight away is particularly difficult and costly. There was a time when this idea had an element of reality, but this is no longer the case. Unfortunately, belief in this myth is shared by those in positions of influence. This paper serves to document that this reality no longer holds, although the misconception may have been based on fact in the past. Whilst the survey of the available technology offered concentrates on electricity supply it also documents that manufacture of synthetic methanol, via hydrogen obtained by electrolysis of water and $CO_2$ integrates smoothly with electricity grid stabilization.

The role of CCS, in practice: mainly capture from the air and industrial processes other than power generation, is reviewed against the background of the cost effective generation of electricity by harvesting renewable forms of energy.

**Keywords**: emissions, climate change, methanol, transport fuel, ocean acidification, CCS

## The myth
The following quotes may serve that this myth is widely held to be a reality.

> "Whatever we decide on in terms of our reliance on renewables, the intermittency of solar, wind and other green sources means that "[….] the more we invest in renewables, the more standby capacity we will need. [….] Because the only electricity capacity that can be turned on and off at will is gas-fired, for every gigawatt of renewable capacity, we need the same amount of gas-fired." (Knight, 2014)
>
> " […..] alternatives to fossil fuels are not yet available at scale for heat and transport, or for electricity production on demand."  (Younger et, al 2014).
>
> "[…]  simulations make heroic assumptions — such as almost immediate global cooperation and widespread availability of technologies such as bioenergy carbon capture and storage methods that do not exist even in scale demonstration." (Victor and Kennel, 2014)

These individuals are in positions where one would have expected them to be familiar with the latest technological knowhow: Angela Knight is chief executive of Energy UK, the representative body of the UK's energy suppliers; the authors of the 2014 letter to The Guardian (Younger et al) are all professors in science related fields whilst the lead author lists his teaching field as energy engineering, and one of his co-authors is Director of the Scottish Universities Environmental Research Centre . Victor and Kennel took it on themselves to write a letter in Nature in which they argue that the 2 degrees target is to all practical purposes unattainable.

Yet I find myself having to insist on the basis of the documentation below, that this perceived difficulty is based on incomplete information: Newer, more effective methods are always welcome, but there are existing technologies which can be used to replace fossil fuels rapidly by renewable energy.

## The renewables technology exists

It is clearly true that the intermittency of the supply of readily harvestable forms of renewable energy such as wind, sunshine and rainfall, presents a complication. There are nevertheless two approaches towards overcoming this difficulty: long distant transport of energy and local storage.

### *Electric power supply for densely populated affluent countries*

IEA-REDT (2013: 20, Fig. 2) emphasises the fact that transport of electric power via a grid provides a more stable supply, as it serves to pool the input from a number of sites. This is the case, even if the type of renewable energy harvested happens to be the same on all sites concerned, which in the IEA-REDT example happens to be wind.

For a medium sized country with a long coastline and strong tidal currents between the coast and various islands, like the UK, something similar applies for tidal power: provided the internal national grid can handle the transport of energy in the form of electricity. There is always a tidal current *somewhere*. Just placing turbines on the bottoms of various current carrying sea passages and pooling their power supplies is sufficient to provide a measure of base-load. But clearly, this is a resource which is not available to landlocked countries.

Before we discuss the role of long distance transport of electric power, it is useful to mention a requirement for the regional supply of electricity in the form of Alternating Current (AC): *synchronization*. The transmission along high voltage AC power at a specific frequency in a limited geographical area is to all practical purposes instantaneous. Power stations, wind farms end AC converted power from solar panels on roofs of dwellings, offices and farms therefore have to supply all be at the same frequency, voltage and in phase with each other. If they don't, they will lose their connection with the grid:

> "The intertrip services are required as an automatic control arrangement where generation or demand may be reduced or disconnected following a system fault event to relieve localised network overloads, maintain system stability, manage system voltages and/or ensure quick restoration of the transmission system." (National Grid balancing services, undated)

This implies that a wind turbine which has to operate under a range of windspeeds cannot vary the speed of rotation of the related generator with the speed of the wind. That is quite visible when seeing a windpark from a distance: All the turbines have a blade at the top at the same time. Although gears can be used to change the speed of the wind turbine whilst keeping the speed of the generator constant, grid connected wind turbines generally have mechanisms to capture only a part of the potentially available energy. An obvious way to do that is to adjust the angle of the blades of the turbine, a technique called "furling" (Wikipedia, 2015a). There are other requirements such as matching voltage and more sophisticated means of meeting these. See Blaabjerg et al (2006).

We now come to discuss the role of transporting energy via High Voltage Direct Current (HVDC) cables and their integration with regional AC grids. Energy may be transported from where it is naturally easy to harvest to where it is needed. This is a role which was in the past and still is, on a massive scale applied with fossil fuels transported in bulk by $CO_2$ generating transport, such as tankers or bulk carriers loaded with coal. The alternative method of ensuring a reliable supply at the time needed is for renewable forms of energy (in practice electric power in particular) by means of a HVDC cable connection. There are basic physics reasons why the more usual AC system of electric current transmission gives rise to more losses at high voltages over long distance than its HVDC equivalent would. Another advantage of the HVDC technology is that it bypasses the need to synchronise regional grids:

> "HVDC permits the asynchronous interconnection of networks that operate at different frequencies, or are otherwise incompatible, allowing them to exchange power without requiring the tight coordination of a synchronous network." (United Nations, 2015: 15)

Clearly the inverter which transforms Direct Current energy into AC supplied to a regional grid also has to meet the requirement of synchronization with the grid to which it supplies additional power. The advantages of long distance transport of electricity via the HVDC technology and its integration with regional AC grids may be summarized as follows:

- Renewable forms of energy can be harvested where and when they are naturally abundant, e.g. solar energy in deserts and in the middle of the day in more temperate zones as well as geothermal energy in volcanic areas and then used where required.
- Pooling of resources: supply across time zones reduces the maximum capacity needed to meet peak demand.
- Installations can normally be used at a level close to their maximum design capacity whenever the local supply of renewable energy such as sunshine is available. When the local supply exceeds local demand the energy is available for use or storage elsewhere, while demand may be met by energy import in case of insufficient local supply.

The modern form of HVDC allows power transmission between or in regional AC grids without a requirement of synchronization or even equal voltage or frequency. It was developed in the 1930s. (Wikipedia, 2015b)

. The 1960s, HVDC transmission system has become a mature technology able to play a vital part in both long distance transmission and in the interconnection of systems.

> "New converter designs have broadened the potential range of HVDC transmission to include applications for underground, offshore, economic replacement of reliability-must-run generation, and voltage stabilization." (Bahrman and Johnson, 2007)

The first 160 MW HVDC link between the UK and continental Europe became operational in 1961. Its trench in the North Sea bed was, however, not deep enough to prevent damage from fishing trawls and anchors. The link was therefore decommissioned in 1984. A new 2000 MW replacement became operational in 1985 Wikipedia (2015c). This connection appears to have pre-empted the need for more installed capacity on both sides of the Channel.

> "The 2000 MWe cross channel link HVDC connection between the British and French networks has saved both countries from power supply emergencies over the years. It probably sidestepped the need to build two more large nuclear units on both sides of the channel." (Modern Power Systems, 2001).

The fourth link across the Skagerrak between Norway and Denmark has recently been completed (Zacks Equity Research, 2015). Norway hopes to utilise its geography, which is particularly suitable for the development of pumped storage systems so as to become "Europe's battery." The presence of no less than four cables below what is basically the same stretch of water also makes it easier to reverse the direction of energy transport (Fairley, 2014). A refinement of the hydro electric technology as now increasingly used in Norway is the use of tunnels rather than pipelines between the upper reservoir and the lower one. These tunnels are not as visible as pipelines and often have a "surge chamber" a cavern inside the mountain near the power station. These can, via their ventilation tunnel to a much higher level accommodate sudden changes in water pressure to facilitate rapid start-up and shut-down of the turbines, (Phys.org, 2015a)

For a map of existing HVDC connections in Europe see the Wagner (2010)). Note that the direct link between the UK and the Netherlands, marked as under construction on this map, became operational on 1 April 2011 (National Grid, 2014). In addition, a direct 1400 MW link diagonally across the North Sea between Blyth in Northumberland and Kvilldal in southern Norway has now also been agreed between the UK grid managing authority National Grid and its Norwegian equivalent Statnett (National Grid, 2015; Statnett, 2015). This means that UK electricity users as well as producers can now also benefit from storage facilities on the continent, in order to balance uneven domestic supply capacity. A fourth HVDC link between the UK and the continent between Richborough in Kent, UK, to Zeebrugge in Belgium has now also been agreed. This link will use HVDC plus the latest technology developed by Siemens, which cuts the energy loss in conversion to only about 2 percent (Siemens 2015) The announcement of this 400 000 Volt HVDC link by the joint body between National Grid and its Belgian counterpart Elia (Nemolink 2015) specifically says: “The link will increase energy security for both countries and support integration of renewable energy.” The cable will use cross-linked polyethylene (XLPE) a special electric isolation material (Sumitomo Electric Industries, 2015). This is a material developed by ABB which is suitable for extremely high voltages (ABB 2010). (The name ABB arose from the merger of the Swedish electric power company Asea (Allmänna Svenska Elektriska Aktiebolaget) and the Swiss company Brown Boveri and Co.)

An internal UK 600 000 Volt HVDC link is now also in the process of being built by NGET/SPT Upgrades Ltd, a joint venture between National Grid and its Scottish counterpart, Scottish Power Transmission. The main purpose of this link is to transport renewable energy from Scotland to England and Wales. As it will be bi-directional (Modern Power Systems 2014), this link will clearly improve the stability of power supply on both sides of the border.

Ashley Seager of The Guardian already called attention in 2006 to the relevance of the HVDC technology if energy from solar collectors in the desert had to be transported to where it would be needed. (Seager, 2006). See also Heesterman and Heesterman, 2013: 246, as well as Desertec-UK, 2013 -or later update-).

Whilst it is Europe where a reliable full scale almost continent-wide HVDC *supergrid* has come nearest to being a reality, long distance HVDC links have been built on all continents except Antarctica (Wikipedia, 2015b).

## *Local storage*

Until relatively recently, the only method of storing large amounts of energy without causing a substantial increase in the cost of reliable supply at all times, was pumped storage. This method of energy storage makes use of the potential of certain types of turbines to double up as pumps. It requires two bodies of water, such as an upper and a lower reservoir, normally two lakes. If the water runs from the upper reservoir through the turbines into the lower one, the turbines work in hydro-electric mode and produce energy. If the direction of the current is reversed, the turbines act as pumps and use energy to pump water from the lower into the upper reservoir. Examples in the UK are the Ffestiniog plant near Trawsfynydd in Wales and Cruachan in Scotland.

Some countries have the good luck of having the conditions suitable for harvesting renewable forms of energy and pumped storage independent of water supply close to each other, as may be illustrated from the following quote from Phys Org [i]'(2015b):

> "Building a $400-million hydroelectric power plant in the world's most arid desert may seem like an engineering debacle, but Chile sees it as a revolutionary way to generate green energy. The idea is to take advantage of the Atacama Desert's unique geography to solve one of the most sticky problems of renewable energies like solar and wind power: inconsistency.
>
> The sun is not always shining and the wind is not always blowing, but in long and narrow Chile, there are always mountains next to the sea.
>
> Chilean energy company Valhalla wants to use solar power to pump water from the Pacific Ocean into two reservoirs high in the Andes mountains. Then it will be allowed to rush back down into a hydroelectric plant with a capacity of 300 megawatts—enough to power three provinces in Chile, a net energy importer that relies mainly on fossil fuels."

Marianela Jarroud of Intrerpress Servive of IPS News Agency (2016) also provides cost information:

> '"Nowhere in the world have they managed to offer clean energy 24/7 at competitive prices, without subsidies," said Juan Andrés Camus, general manager and one of the two founders of Valhalla Energía, the local company that is carrying out the project.'

However, the cost of storage of energy by means of batteries is now coming down sharply. Relatively cost effective technology, using salt water to that purpose is now available Aquion (2013) launched what is in effect a sodium sulfate battery. The use of sodium sulphate by Aquion should not be confused with the combination of molten salt and sulphur, which achieves a much higher energy storage per volume but gives rise to other problems as some applications of this technology are highly corrosive and toxic (Orikasa et al, 2014).

A smaller firm in my native Netherlands (Ten BV, now marketing as Dr. Ten) has been testing a prototype of a battery suitable for integration with micro generation for some time (Ten Kortenaar, 2013). It now intends to build a factory to start mass production (Simons, 2014 (in Dutch)). The firm now also advertises its salt batteries, with some technical information:

> "The sea salt battery is a battery consisting of minerals, carbon, and salt extracted from natural sources. The battery is constantly being improved and currently has a energy density of about 30 Wh/kg and a cost price lower than any existing battery" (Dr. Ten, 2015).

A group of chemistry specialists at Harvard University in the US developed a battery using a chemical compound called AQDS (9,10-anthraquinone-2,7-disulphonic acid) for which prototype tests indicated that it can efficiently store electricity. The elements in this compound (Sulphur, Hydrogen and Oxygen) are all abundant in nature. This is, in combination with Bromium and water, the liquid part of the battery. The other components are a membrane made of Nafion, a compound consisting of the elements

Sulphur, Carbon, Fluor, Oxygen and water, i.e. also materials which are relatively abundant in nature, and carbon electrodes. The authors (Huskinson et al, 2014) expect this to be a cheap way to store electricity at any required level.

A parallel briefing paper by the School of Science and Engineering of Harvard University Harvard University School of Engineering and Applied Science (2014) suggests that this type of battery could provide adequate energy storage for normal household use within the size of basement or loft hot water tank and also, when built on a larger scale be capable of supplying the power output and response speed which would make it suitable for grid stabilization.

Clearly there is a range of not too costly batteries now being developed and even marketed.

In Germany, two pilot plants built to test the storage of energy in the form of hydrogen produced by the by electrolysis of water have been operational for some time. These facilities use a special membrane, called a proton exchange membrane in order to facilitate rapid fluctuations in the production of hydrogen in response to changing supply of windpower. The hydrogen can then be combined with $CO_2$ to produce methane, which can be fed into the gas grid. The first production scale plant of this design with a capacity of bridging up to 6 Megawatt local surplus of electric power supply over local demand is now operational near Mainz. (Energie Park Mainz 2015). There is no mention of methane in this press release. However, there is reference to the P2G (Power to Gas) technology in both the initial report of the two pilot plans (Hampton. 2013) and in the above mentioned press release by Energie Park Mainz. Clearly at least a part of the hydrogen generated at the Energie Park Mainz is or could in the future be used to produce methane the gas grid.

An additional bonus is the circumstance that methane can be processed into methanol (Gondal, Hameed and Suwaiyan, 2003). Methane is not very suitable as motor fuel because it normally occurs in gas form and becomes liquid only at either very low temperatures or high pressures. Its storage and transport in bulk is therefore not straightforward. By contrast, methanol is liquid under atmospheric pressure and ambient temperature. Engines able to run on methanol for maritime shipping are being built already. These engines can run on a range of fuels. However, the reason for ensuring that they can run on methanol appears to be the expectation that tighter regulations on conventional pollution by maritime transport are coming (Marinelog, 2013). So far the most common source of methane to produce methanol is (fossil) natural gas (Course Hero 2015). However, these engines could obviously also run on purely synthetic methanol or methanol made from biogenic methane. Methanol has a somewhat lower caloric value than petrol-like fuel while the higher water content of its combustion product also means that it is more corrosive. Nevertheless model aircraft and racing car engines running on methanol have been built (Wikipedia, 2015c), hence we may reasonably assume that the construction of ordinary motor car and aircraft engines is feasible. Aircraft fitted with a car engine were also built (Pope, 2015). This article also explains that a main difference in the requirements to be met by a aircraft and motor car engines is reliability:

> "Try running your car's engine at or near redline rpm all the time and see what happens. Of course, we don't know what will happen, and in an airplane we can't pull over to the side of the road when it does."

This argument needs to be qualified. Aircraft normally have several engines and can keep flying if one of them fails, but this tends not to be the case for ships, even whilst a failed engine and gale force wind blowing in the direction of rocks spells serious trouble in case of a ship. is in Yet ships equipped with engines capable to be run on methanol -and intended to be used as such- are being built without multiple engines, as far as I can make out from Marinelog (2013).

In urban traffic the use of methanol has as automotive fuel also has the important advantage of being a relatively “clean” fuel. The (USA) EPA (Environmental Protection Agency, 1994: 2) lists its benefits as being an “Excellent automotive fuel” and “Very low emissions of ozone-forming hydrocarbons and toxics” even whilst mentioning its “*Somewhat* lower vehicle range” (Italics put by ARGH) as a disadvantage.

An actual advantage of methanol over aviation kerosene as so far usually used is its low freezing point. Pure methanol freezes at atmospheric pressure at -98 degrees Centigrade below zero. As methanol is hygroscopic, some degree of contamination with water cannot be entirely avoided, despite careful storage. However, at 90% purity, the freezing point is still -90 degree C. (The Engineering Toolbox (undated)).

By contrast, aviation kerosene as currently usual needs either special processing to stay liquid at low temperatures, or aircraft design features to prevent the fuel from becoming too cold.

> “Jet fuel is exposed to very low temperatures both at altitude – especially on polar routes in wintertime -and on the ground at locations subject to cold weather extremes. The fuel must retain its fluidity at these low temperatures or fuel flow to the engines will be reduced or even stop.” (Chevron USA, 2007)

The view of the aviation industry (as far as there is any) appears, however, either to be that hydrogen is the best option, citing its low weight to energy content as a main reason (Kojima, 2014)

The view of the aviation industry (as far as there is any) appears, however, either to be that hydrogen is the best option, citing its low weight to energy content as a main reason Kojima, 2014).. I also found at least one publication expressing reservations against methanol as aviation fuel (Saynor, Bauen. and Leach, 2003). These reservations concentrate on the toxicity of methanol in its unburnt form its low flashpoint its relatively low caloric value and its cost in comparison with natural gas. There was even then no suggestion that it could not be used. I do not claim the expertise to judge the relative merits of methanol versus hydrogen, but it is clear that there are alternatives to continuing to use fossil fuels even for aviation.

Clearly, the direct use of renewable energy harvested in first instance in the form of electricity is a more cost effective use of the harvesting equipment than the roundabout route via hydrogen, $CO_2$ taken out of the air and conversion of methane to methanol. Nevertheless, unless more cost effective alternatives are found, we may reasonably assume that methanol is the renewable fuel of the future wherever direct use of electricity is impractical.

Lead acid car type batteries can also make a significant contribution to the effectiveness of domestic roof mounted solar panels, reducing the strain on the grid in the process. A UK company is now marketing a pack of such batteries with a storage capacity of about 4.5 Kwh and associated software to optimize a house’s demand from and supply to the grid over the day and the night (Powervault, 2015). In addition, the cost of batteries using lithium compounds and graphite have decreased drastically whilst their durability has increased. US car manufacturer Tesla Motors also markets (lithium) batteries for home storage of electricity from solar panels (Tesla Motors, 2015). A US company Alevo, now plans to build America's largest ever energy storage system, a battery to the purpose of grid stabilization (Murray, 2015). A smaller version of a similar type of battery of ‘only’ 6 Megawatt is now being tested at Leighton Buzzard in the UK. (Houses of Parliament UK, 2015: 2) This report also contains a summary of a range of electric power storage technologies. Some more technologies can also be found in Wright (2015).

## HVDC supergrids, connected grids, local storage and bi-directionality

Dr. Czisch (2011, front cover) appears to envisage a HVDC supergid: a single system of fully integrated high voltage cables which supplies the same 600 KV (Ibid: 203) high DC voltage over a wide geographical area. There are, however, several possible drawbacks to this concept.

First of all there is a technical issue. It appears that interrupting HVDC current is more complicated than it is for its highvoltage AC equivalent, a problem which, unless solved, may reduce reliability of supply.

> "[….] for an interruption to occur safely, any DC link first must be disconnected from the AC side of the converter. This is acceptable for point-to-point DC links but likely unacceptable for DC networks, as it means de-energising the whole network if a fault affects any of the lines." (IEA-REDT, 2013: 33)

Although manufcturers indicate that this issue has been resolved by the development of suitable HVDC power interruption switches, IEA-REDT remains skeptical:

> "As of early 2013, major manufacturers claim to have developed high voltage DC circuit breakers, yet the HVDC breaker is not yet available commercially and remains a new and largely untested technology." (*Ibid*)

There is an obvious basic physics reason for this skepticism of IEA-REDT: If you open a circuit breaker in a power connection which carries, say 1200 MW of power as DC, the first result is a spark flame which will vaporize and burn the metal, while the flame will continue in ionised metal vapour until the gap is much wider. The balance of my judgment is that a combination of HVDC-linked AC grids, with the storage capacity to continue to supply normally for at least a few days, is preferable in comparison to the fully integrated HVDC supergrid, and not only for this particular reason. The most suitable arrangement might well be an adequate storage capacity in batteries associated with micro-generation, which is currently in practice dominated by the energy from photovoltaic solar panels. As these supply DC they need in any case an inverter to supply power to AC devices such as washing machines etc. If such micro generation systems were programmed to keep half their storage capacity in reserve for emergency support of the regional AC grid, this should keep AC grids working as normal even if their linking HVDC connection(s) were shut down temporarily (see also Del Granado et al (2014). Note however, that these authors consider the battery only as a means to reduce demand *from* the grid without mentioning the potential of its use in order to support a regional grid in the event of an interruption supply *to* it. The latter would of course require special programming to instruct batteries of micro-generation systems to start supporting the regional AC grid. A group of linked AC grids should normally have at least two connections between any two linking hubs, so that it could be re-activated as soon as a damaged or otherwise defective cable had been disconnected. Laying two different cables along different routes clearly enhances reliability and has been in use for some time (Praça et al, 1996: 2).

The other drawback of the HVDC supergid arises from the fact that it involves significant overhead cost, both in the environmental sense, giving rise to forest destruction because of the need to lay cables, and any necessary road building as well as in financial terms. Clearly in the case of relatively thinly populated counties and areas with a so far low energy use per person, isolated local storage is likely to be preferable over any kind of grid.

Whilst battery storage helps to overcome an inherent limitation of the HVDC technology, it also is useful in overcoming a limitation of many AC grids: their inflexibility to smoothly and quickly change the direction of power supply.

> “As the number of solar panels on business and rooftops multiply, America’s power grid is bearing an electrical load that it was never designed to handle: bi-directional power transfer.” (Maerian, 2015)

A modern grid can and should have an adequate capability to transfer energy as required. Such a capability has, to a degree the same advantages of pooling resources as the HVDC technology has for even wider geographical areas. However, as the quote illustrates, this is as yet not always the case.

## The cost effectiveness of renewables

As far as electricity supply is concerned, this issue was investigated in the afore-mentioned 2005 German thesis, translated into English in 2011 (Czisch, 2005, 2011). By now, the generation of renewable forms of electricity may well be more cost-effective than the build of additional fossil fuel capacity, even at the prevailing false price structure with its virtual absence of a market cost for emissions. This is so in particular for densely populated and affluent areas.

Dr. Czisch optimised the most cost effective supply structure for Europe and neighbouring North Africa and Central Asia. He started from a reference scenario based on renewables only and then considered a number of alternatives. He found that gas fired Combined Heat and Power (CHP) (referred by Czisch as CCGT (Combined Cycle Gas Turbine) was the one notable exception to the optimality of the ‘renewables only’ position (Czisch, 2011: 278 ff.). This related to 2001 gas prices, which led him to question the relevance of this qualification in view of the 2001-2005 rise in gas prices. Gas prices have since risen even more, and came down again. What does, however, render this caveat open to discussion is that Czisch (2011: 279) explains that photovoltaic solar power is the type of power supply for which the optimal level was drastically reduced by bringing in CHP.

Czisch’s latest actual cost data for this type of equipment date also from 2001 (Czisch (2011: 24, Table 4.1). Since that time, the cost of PV cells has roughly halved (Feldman et al 2012: vi, graph), and is expected to fall even further (Ibid: 15). In the UK, the cost per KWh of onshore windpower has been essentially stable, whilst that of offshore windpower has significanly increased (Irena Secretariat, 2012: Fig. 6.6 on p. 47). One reason for this increase is the one mentioned by the Crown Estate (2012: Executive Summary, vii) the move into deeper water.

There are, as far as the conclusion that reliable power supply from renewbles only could actually be *cheaper* than fossil fuels is concerned, several qualification to be made: Even whilst battery storage of large volumes of electric power may now be in the offing, Dr. Czisch did not take the further additionl costs of local storage and duplicate cabling to the capital cost of a HVDC supergrid into account. These methods of enhancing the reliabity of supply are clearly desirable. However, relatively cheap energy storage was largely unknown in 2005, apart from the exception of pumpted storage in mountainous regions. Also, he did not appear to have considered the cost of providing more than one cable between the same two points as a safeguard against power supply interruptions. In addition, Czisch (2011: 204) assumed the use of pylons for HVDC cables as is usual with AC high voltage power lines. For the much higher voltages now being used for HVDC connections, insulated cables burried in trenches are clearly preferable, for reasons of safety and reliability, as well as to avoid energy leakage in ionised moist air. Such connections would, however, be more expensive.

Nevertheless, at least one reference basically confirms Dr. Czisch’s findings rather than really adding to it. A joint report by the accountants firm PriceWaterhouseCoopers, the Potsdam Institute for Climate Impact Research and the International Institute for Applied Systems Analysis (2011) opens its introduction with the statement:

> “Climate change and increasing demands for affordable energy are two of the biggest challenges faced by society today. With appropriate scale, a shift to renewable energy could become a self-

> sustaining, and genuinely competitive investment proposition with the potential to address both of these concerns.” (listed in the references as by PriceWaterhouseCoopers)

It also flags lack of effective international cooperation as an obstacle:

> “The transition to renewables relies heavily on the development of an international, and subsequently an intercontinental, transmission grid. However, today it is barely possible to build a single transmission line, especially across national borders, as a result of inefficient regulation and public opposition. There is an urgent need to increase political cooperation between countries, to improve the efficiency of legislation and permission processes for new transmissions projects.” (*Ibid*: 8)

One curiousity I came across at in this context is a complaint in *The Engineer* by Nathan (2012) that network operators are not allowed to own generating capacity whilst storage capacity is classified as generating capacity.

> “ ‘I’ve been looking into this, and it’s a bit like a carousel,’ he said. ‘I asked the generators if they’d be willing to build storage capacity, and they don’t think it’s their responsibility; they think it’s a network function. And if you ask the network operators, they say that government regulations say that they’re not allowed to own generating capacity and storage, ironically, is classified as generating capacity; but if someone were to offer it as a contract service, such as a demand aggregator, they’d be happy to pay for it. So I spoke to them, and they said they’d be happy to offer the service, but they aren’t in the business of investing in capital-intensive equipment and the intermittency wasn’t their problem, so why didn’t I talk to the generators? And so around it goes.’ “ (Nathan, 2012).

Somewhat to my surprise, The World Wildlife Fund (2011) also consides 100% rnewables by 2050 cost effective, even whilst the stirngs “HVDC” and “Direct Current” do not figure in that report.

There has recently been a steep drop in oil prices which fell from more than $100 per barrel in July 2014 to under $50 in January 2015. (Austin, 2015), whilst the price of gas has also fell, a circumstance which might one conceivably lead one to question the commercial viability of a rapid replacement of fossil fuels by renewables. However, of the six reasons why this author expects no soon recovery in the oil price, one is the increase in energy efficiency and investment in renewables, a tacit acknowledgement of the commercial viability of renewables. I also have my doubts as to his expectation that the Islamic State will soon be suppressed and normal oil production in Syria, Iraq and Lybia resume: Bombing is not the most effective way to restore normality. He also argues that “fracking is not going away”. Maybe. However, whether or not there is a substantial risk of unburned methane from fracking operations leaking into the atmosphere, the (United States) Environmental Protection Agency is now demanding systematic on-site monitoring of such leakage (Magill and Climate Central, 2015). I strongly suspect that this monitoring as well as effective measures to ensure absence of leakage will significantly increase the cost of fracking. And there were already questions about its cost effectiveness prior to this requirement: many smaller companies incurred debts in the expectation of higher gas prices which they now cannot repay. They are now likely to be taken over by bigger firms (Eaton, 2015). I gather from Leggett (2015: 175-176), referring to the Financial Times (2014) that a sizeable part of these debts of smaller oil companies could remain unpaid debt to banks. The major oil companies may have more substantial reserves, but at an oil price of $80 per barrel or lower, they are thought to be unable to repay the debts they have incurred to pay for exploration and development whilst expecting higher oil prices. (Katakey and Casiraghi (writing for Bloomberg), 2015). Yet for individual oil companies producing and supplying less oil is no solution: the money (half a trillion dollars) has already been spent and must be repaid. One of the two: Either these low oil prices won’t stay, or oil companies will be going bust.

Whilst I would not be sure whether electricity supply via renewables only is already cheaper in strict commercial terms than using fossil fuels, I nevertheless beg to differ, with due respect to these distinguished authors, with King et al (2015: 5), who state:

> "Third, renewable energy can never replace base-load fossil-fuel powered electricity unless it can be stored more cheaply."

In my opinion, their emphasis on the need for more ***research*** is misplaced. It is time to build the renewables energy infrastructure, whether or not it might at the moment appear to more of a financial burden than continuing to cook the planet.

## The urgency and pace of decarbonization

Even the most stringent emission reduction scenario investigated by the IPCC (RCP2.6) only considers it *likely* that more than 2 degrees global warming will be avoided (IPCC 2013: 20). The carbon content of known and commercially exploitable fossil fuel reserves amounts to about five times the amount that can be burned whilst still having about a 50% chance of keeping global warming within the 2 degrees maximum limit agreed at Copenhagen (Carbon Tracker and Grantham Research Institute, 2013).

In addition, there are questions about the adequacy of the 2 degrees limit mantra. Hansen et al (2015: 20068) report evidence of superstorms during the previous interglacial, the Eemian (also knwn as marine isotope stage 5e), when the earth was warmer, but most definitel not by more than 2 full degrees Centigtade above Holocene levels:

> "[….] wave runup deposits that reach heights nearly 40m above present sea level, far above the reach of a quiescent 5e sea surface."

This quote refers to a boulder thrown high on dry land by a hurricane on an island in the Caribbean. Hansen puts the sea level during the Eemian at its highest at 9 metres above its current level (a higher estimate than I ever saw elsewhere, but that still leaves waves capable of throwing a bolder more than 30 metres high up the beach.

IPCC (2014b) mentions a number of limitations of Integrated Assessment Models, and by implication about the responsibility of burning even as much as 20% of the known reserves. Such models do not really quantify adequately what climate change does to human beings. These comments on model limitations concentrate on two issues: the risk that the effects of climate change could be much worse than the central (average expected) forecast for any emissions scenario. Thus, the avarage increase in the temperature is likely to be no more then 1.9 degreed under RCP2.6, but IPCC does not not exclude that it *could* be more. The authors of this report are clearly aware of the issue of food security, although this concern is not quantified or linked to action on containing emissions. The omission of reference to food security is another basic element of inadequacy of the integrated assessment models as so far used: the aggregate global GDP approach does not consider the consequences of climate change on the global food supply.

For even higher temperatures under "business as usual" there is now a warning that by 2100 large swaths of SW Asia could have lethal temperatures. Whilst press reports (Carrington, 2015) emphasise the possibilty that hadj pilgrims to Mecca could find a day of prayer in the blazing heat of the desert a direct entry to Heaven, the source article (Pal and Eltahir, 2015) refers to the wider SW Asia region and in particular around the Arabian Gulf.

Lord Stern (2006/2007) was criticised by Byatt et al (2006: 203) for giving undue weight to to agricultural production.

> "Most of the world's economic activity today takes place indoors: generally speaking, the outputs of both manufacturing and services are unaffected by outdoor conditions."

This criticism of Stern is deeply flawed. Although food consumption amounts statistically to only a small fraction of the value of global consumption spending if measured in financial terms, it is of critical importance. The precise figure is in any case questionable because there is no statistical record of either subsistence farming in poor countries or allotment and private garden cultivation in affluent economies. The financial valuation is further distorted by low wages and low food prices in the poorer part of the world. Anyhow. let us put that fraction at say 10%.

Now assume that global food supply drops by 10% of its former quantity, a figure which is according to Tai, Martin and Heald (2014: 817) a conservative estimate of the consequences of 'business as usual' by 2050. If so, a 20 percent increase in the supply of non-food consumer goods combines statistically with a 10% drop in food consumption as a 17% increase in total global consumption. The consequence is, however, that rich people spent a part of their increased income on paying more for their food, whilst large numbers of poor people go hungry!

In addition Hansen et al (2013) are of the opinion that the 2 degrees limit is already beyond the danger point where not only the results could be catastrophic, but where it also implies even *more* warming in the more distant future.

Two further issues need mentioning. One is that the enhanced *level* of the $CO_2$ content of the atmosphere means that even when it starts to decrease gradually, the oceans will continue to warm up further for several decades. The worst horrors of climate change are therefore likely to become manifest only after mid-century. The other is that these estimates are global. Adequate compensation for the victims of climate change in certain regions, is a social-political obligation for the more fortunate parts of the world, which is likely to meet with even more serious reservations than a decision to rapidly replace fossil fuels by renewable energy would. To make this point clear, it is perhaps useful to quote a passage from the report of IPCC's Working group 2:

> "Climate-change-related risks from extreme events, such as heat waves, extreme precipitation, and coastal flooding, are already moderate […..] Risks associated with some types of extreme events (e.g., extreme heat) increase further at higher temperatures." (IPCC 2014c: 12)
>
> "Major future rural impacts are expected in the near term and beyond through impacts on water availability and supply, food security, and agricultural incomes, including shifts in production areas of food and non-food crops across the world." (*Ibid*: 19)

Clearly this is the kind of development which we certainly want to prevent getting even more serious. It is against this background that I argue that burning even the 20% of known fossil fuel reserves could be irresponsible, if it can at all be avoided. The outlook for realising this aim does not look too good, for socio-political rather than technological reasons.

What should also be borne in mind is that climate change is not the only potentially disastrous result of coninuing to burn fossil fuels:

> "The scientific community overall has a high degree of confidence in our general understanding of the dominant controls on ocean chemistry over periods of 10,000 years or more, and thus can say with a high degree of confidence that ocean acidification predicted to result this century as a result of "business-as-usual" emission scenarios would be geologically anomalous and that no similar event is known to have occurred for at least the past 50 million years". (Caldeira, 2011: 99)

The aim should be to, if at all possible, be reasonably certain that this level of global warming and the risk of catastrophe it could bring with it, is avoided. Anderson (2013) insists that to avoid dangerous climate change a policy is required of zero $CO_2$ emissions by around 2040. To achieve this, emissions will need to peak by about 2020 and then start reducing by around 20 percent per year. In my view this is quite doable; see above for the technological information. Nevertheless, the potentially disruptive socio-economic side effects of such a course of action need to be anticipated and cushioned.

Already in 2012, the fossil fuel infrastructure in place, power stations, factories etc., implied that more than 80% of the fossil fuel that is thought to cause full 2 degrees of global warming was "IE in" i.e. would be burned if these installations were to remain operational during their normal expected operational life span. (IEA, 2012: 241). That relates to having a fair chance to avoid more than 2 degrees of warming above pre-industrial levels. To avoid the likelihood of the kind of superhurricanes which occurred during the Eemian (see above), it will be necessary to restrict emissions to even less and existing fossil fuel using equipment may have to be abandoned before the end of its technical life span. If exploitation of fossil fuel is limited to one fifth of the known reserves or to even less, banks, insurance companies and pension funds will have to write off a part of their 'assets'. This applies to fossil fuel reserves as well as to facilities based on the use of fossil fuel use, such as coal fired power stations. This is an additional cost of past investment in a technology which should have been regarded as obsolete, being based on burning fossil fuels. Such a development could result in major problems for the affected banks and insurance companies with respect to meeting their obligations to creditors and retirees. Measures may be needed to ensure that pensions are paid and the repair of flood or storm damage is financed, even whilst pension funds and insurance companies may have had to write off a substantial part of their reserves. Also, what must not happen is that mortgage providers are forced to repossess residential property because the borrower has been made redundant while the lender would have been confident that the loan and its arrears would eventually be repaid in full once the borrower had found another job.

In addition, people working in these industries will lose their livelihood, an issue which could hit certain countries very hard indeed. At the moment more serious job cuts are being pre-empted by environmentally unsustainable practices. For example, management at the Grangemouth petrochemical refinery complex in Scotland assured its workers that, although two sections of the complex were to close, there would be no job losses because ….. it planned to import large amounts of shale gas from the US (BBC News Scotland, 27 March 2014).

The global dimension of this issue as warned for by IPCC (2014a:17), loss of export revenue of fossil fuel exporting countries is beginning to give rise to global financial problems. This issue is now becoming critical in the case of Saudi Arabia:

> "The decline in oil prices is resulting in substantially lower export and fiscal revenues. A central government fiscal deficit of 19.5 percent of GDP is projected in 2015, and while the deficit will decline in 2016 and beyond as one-off spending ends and large investment projects are completed, it will remain high over the medium-term." IMF (2015: 2)

Cushioning the short term effects of this Saudi deficit, and no doubt of that of other oil producing countries, both for Saudi Arabia and for the global financial system, which will be faced with large withdrawals of funds from banks in the rest of the world, is the task of the IMF. The IMF seems to think that Saudi Arabia can in the longer term adjust to the resulting situation by expanding its private non-oil production sector. I have my doubts as to whether that is practical, and even more so, whether this should be predominantly the private sector. The country could presumably become a large scale exporter of solar power, but that is typically an industry which requires major infrastructure investment, which would be more suitably managed by the state. The IMF expressed its approval for the state containing and temporizing its infrastructure investments, but the delay in building a major solar power plant (Bloomberg, 2015) is not helpful for the country's long-term economic viability. I don't see this desert country having much agricultural potential or becoming suitable as a tourist destination for Western visitors, and charging Hadj pilgrims hotel type accommodation costs will not make Saudi Arabia popular with less affluent Muslim countries. The world might have to think about a compensation scheme for the loss in value of fossil fuel reserves, provided it does not reward irresponsible recent exploration.

A comment on the manpower restriction under conditions of rapid decarbonisation is in order at this point. The demand for labour for this that type of investment may be skewed towards workers with scientific or otherwise technology related skills. Nevertheless under market economy conditions effective steps to contain the twin crises of catastrophic climate change and destruction of marine life by ocean acidification imply rekindling economic growth.

There are two main reasons for this. The first is simply that skills other than engineering and construction are needed to contain emissions. Retrofitting existing buildings with proper insulation and helping people with arranging that are not nearly as specialized as the manufacture of wind turbines and solar power stations. The other is the Keynesian multiplier mechanism (Heesterman and Heesterman, 2013: 130*ff*.). The formerly unemployed may find work in the construction and engineering industries, with an improved sense of job security overall. This will give rise to more being spent on leisure activities It may also make the securely employed more inclined to encourage their children to stay longer in education. Once the spell of austerity (see also Krugman, 2015) has been seen to be dysfunctional and hollow, there will also be more work for public sector workers. In short, job seekers without the specialized skills required by the construction and engineering industries will be able to find other types of employment thereby securing more in the way of tax revenue for the treasury. A public sector deficit is the mirror of increased incentives to save and its long-term remedy requires restoring the Welfare State (Heesterman and Heesterman, 2013: 125 ff., 251).

Even so, we are on a global scale still quite some distance away from a binding labour supply limit. There are many millions of refugees and asylum seekers, many of whom possess skills currently in short supply, for instance those from a medical background, who are forced to keep cooling their heels in refugee camps, prevented from putting their knowhow to good use and pay tax, instead having to be supported from the public purse. Whilst the Refugee Council, (2015) puts the emphasis on medical skills, it is clear that there also are other skilled refugee workers. At a time when there was approximate full employment for all, their contribution was critical:

> "Properly qualified refugees and migrant workers play a key role in keeping the passenger transport industries working effectively. We have a serious shortage of skilled workers and without the contribution of migrant workers and refugees as drivers, many of our transport companies will be unable to provide a full service to the public." (Progress GB, 2005, referring to Vicky Ball, the then Director of Workforce Development)

No doubt there are also refugee construction workers, Such skills would come in useful in a rapid build up of the infrastructure and installations needed for decarbonisation at the sort of pace demanded by Professor Anderson. The upside of this issue is that a policy of rapid decarbonisation will, by creating more employment, also make it easier for affluent countries to admit and assimilate these refugee immigrants without too much controversy about any threat to the jobs of residents.

## Substitution of electricity for other forms of energy use

Once a reliable supply of electric power is available, there is a considerable possibility to phase out the use of fossil fuels for other purposes. As far as heating homes, offices and factories are concerned, priority number 1 is insulation. However, beyond that point, electric heating is straightforward.

Electric cars are now also becoming more common. However, the currently prevailing pattern of daily car use raises questions concerning the availability of raw materials, certainly if it were to become more widespread in currently less affluent societies. A summary of the energy densities of the available batteries also gives rise to questions about their usefulness in relation to transport.

| Power supply source: | Energy intensity in watt hour per kg weight: | Reference |
|---|---|---|
| Kerosene: | 12 200 | (TRBP, 2015) |
| Lithium battery | 400 | (Cleantech, 2015) |
| Dr Ten's Salt battery | 30 | (Dr Ten, 2015) |
| Aquion's salt battery | 17 | (Enipedia, 2015) |

These figures suggest a ratio between the energy intensity of fossil fuel and the lithium battery of more than 30 to 1. However, that is a distorted ratio, and the meaningful one is more moderate. The efficiency of the internal combustion engine is much lower than that of an electric motor. In addition, a well designed electric car will recover energy whilst braking, whereas the fossil fuel driven car just discards the energy. Also, the weight of an electric motor is a fraction of that of an internal combustion engine with its several hundreds of kilo cast iron engine block. Nevertheless the above figures make two things clear: (1) The salt battery may be suitable for static energy storage, where its weight does not matter, but is useless for energy storage in vehicles. (2) Unless you are happy to stop several times a day to have your battery re-charged, the electric car is for local urban use only where it can be charged every night at home and at your place of work during the day. For long distance travel a train which gets its energy directly from the grid via the overhead power cable, or if you must have a car, an engine running on methanol, is a more suitable means of transport.

That raises the question whether city dwellers should be using cars at all. These batteries require raw materials which are not nearly as abundant in nature as salt and sulfur. Electric motors, including those used in electric trains and buses, also require other even rarer minerals than the lithium used in their batteries. (Chianelli, 2010). That is nevertheless a complication which is resolvable by a major shift from road to rail and more generally to mains supported electric transport, without the need for too much change in lifestyle. See also the information concerning methanol below. In addition, a daily routine which includes a couple of walks in clean, exhaust fume free air to and from stops of an electric trolleybus, tram or station is much cheaper and might also be much better for city dwellers' health.

As to maritime shipping and aviation, these sectors so far make a relatively modest contribution by comparison with other sources of carbon, about 2.2% for shipping (ICS, 2014 top page), and around 2% in the case of aviation (ICAO, 2014)  Whilst emissions from shipping are falling, those for aviation are rising rapidly. However, shipping emissions tend to contain many serious other pollutants, due to widespread use of cheap and dirty bunker oil.

Several comments are useful in relation other energy use by long distance maritime shipping and aviation.

I stick to my opinion that using biofuels instead of mineral oil is not the solution here, for the reasons explained in some detail in Heesterman and Heesterman (2013: 227-8). There may well be a limited room for genuinely sustainable biofuel such as processing used cooking oil into fuel, but the demand for fuel, just by these industries is so large that replacing a significant part of it by biofuel is either at the expense of food production, or, if more land is converted to growing biofuel crops a cause of large *increases* in greenhouse gas emissions.

There are also chemical processes which can use energy to convert $CO_2$ and water vapour into fuel. However, according to reports regarding the current state of development of the technology the energy content of the fuel produced is less than 10% of the solar energy used. Unsurprising, there is as yet no large scale commercial application (Taylan and Berberoglu, 2013: 60-61). If flying were to be costed on the basis of an energy cost of the fuel which could be quite a bit higher than the cost of renewable aviation fuel (Heesterman and Heesterman, 2013: 179, benchmark technology) that could come near to eventually banning air travel for unessential purposes. The reasons why this is unlikely to be the case are discussed in more detail below.

However, further progress on removing $CO_2$ from the atmosphere, not for underground storage but for industrial use is now being made. A research group at the George Washington University in the US reports as follows:

> "The Licht research group has taken on the challenge of a comprehensive solution to climate change. We're working towards changing today's fossil fuel, to a renewable chemical economy, replacing the largest greenhouse gas emitters, including iron & fuel production by new, inexpensive, solar, CO2-free, chemistries." (Licht, 2015)

The work of this group includes synthetic hydrocarbon fuel (Liu et al, 2015). Licht and Ren (2015) also applied for a patent to use sunlight and $CO_2$ to make carbon fibre and other materials consisting predominantly of carbon for industrial and construction use. If the products in which these materials are used eventually are disposed of in landfill, they would not readily oxidize to $CO_2$. Whether such industrial use of carbon would be enough to make a substantial inroad in the excess of $CO_2$ already in the atmosphere is nevertheless the next question. However, as will be discussed further down, in that case such processes might also be useful as a route towards end-disposal of carbon without the materials being of any further economic use.

For maritime shipping on short routes such as ferry crossings, batteries may possibly be acceptable in terms of weight and volume and charging in port may suffice. Nevertheless, it remains the case that the energy cost of maritime transport is understated by the current price structure, and our comments on globalization (Heesterman and Heesterman 146*ff*) are applicable: There should not be such a huge volume of bulk-carrier transport. This conclusion applies even more to the sharp rise in aviation, in particular because no technological substitute for aviation kerosene derived from fossil fuels is soon likely to be available. Note that, as mentioned above above, biofuels are counter-productive.

However, there now is a much wider possibility to extract organic compounds from biological waste material such as straw, sewage and manure. Biofuel in the form of methane is now well established. For instance a bus powered by biomethane from human waste is now driving around in Bristol (BBC News England, 20 November 2014). In addition, the products of heat-processing these substances include hydrocarbon-like chemicals that can be used as oil (Fraunhofer, 2014; Neumann et et al, 2015). Incidentally, recycling these types of organic matter also opens the possibility to use the remaining ash as fertilizer. That would avoid both exhausting the natural supply of phosphorus and the pollution of rivers and eventually oceans with fertilizer remnants. For a broader survey of the available technologies to make synthetic fuels, see Ferrari et al (2014).

# Carbon Capture and Storage and the price for emissions

This procedure (abbreviated to CCS) means that $CO_2$ is captured and then put stored safely in a place from where it cannot get back into the atmosphere. It has been widely advocated as way of continuing to use fossil fuels as a source of energy. At the extreme end of this view appear to be Victor and Kennel (2014) referred to above, who argue that the target of containing global warming to not more than 2 degrees Centigrade cannot be met without CCS. It can also be applied to the atmosphere, with a view to get the $CO_2$ content of the atmosphere back to a sustainable level, as advocated by Hansen et al (2008).

There are other people in official positions, who envisage CCS from fossil fuel using power plants to play an important role in containing emissions. That issue is clearly related to the valuation of fossil fuel reserves. For example, IPCC (2014a:17) states:

> "Mitigation policy could devalue fossil fuel assets and reduce revenues for fossil fuel exporters, [….]"

However, the same report then qualifies this observation by stating:

> “The availability of CCS would reduce the adverse effect of mitigation on the value of fossil fuel assets”

Again, a correspondent of *The Guardian* Neslen (2015), reports from Brussels not only a call for binding CCS targets, but also refers to the opinion of Graeme Sweeney, chair of the European Technology Platform for Zero Emissions Power, that three quarters of this should come from the power sector. I have seen other similar press reports.

The above mentioned press reports appear relate to a December 2014 paper prepared for the European commission. In fact, that report contains a qualification indicating doubt as to the benefits of CCS:

> “[..] including an assessment of whether or not CCS is required.” (European Commission, 2014: viii Key Points):

My assessment is that CCS would prove to be uneconomic as a route towards continued use of fossil fuel for power generation, as defended by Jaccard (2005), even though it is still clearly needed for industrial applications such as cement and steel manufacture. Its application in areas where storage site of CCS can be handled locally whilst phasing out of local production of fossil fuel would lead to unemployment may nevertheless be desirable for a transitional period on social grounds. The other qualification of the dominance of renewable energy over CCS relates to the Wind Power-to-Gas (P2G) technology mentioned by Hampton (2013) and its integration with electricity grid stabilization discussed above. Whilst eventually net $CO_2$ emissions must be fully phased out (and become negative), retrofitting a fossil fuel plants with CC (not CCS, only Carbon Capture) might in the short term be a more cost effective method of acquiring the $CO_2$ to make methanol than extraction of $CO_2$ from the air would be.

Using fossil fuels with CCS is bound to be more costly than just burning fossil fuels as at present. It also requires additional fuel to generate the energy needed for the process itself. IPCC (2005: 4) provides estimates of these additional energy requirements for power plants in which CCS is integrated with energy production. For gas fired plants this report puts the figure at 11 to 20% additional energy and hence fuel costs to produce the same amount of energy for end use. In the case of coal that becomes 14 to 25%. However, these figures assume full integration of CCS with energy production. Retro-fitting CCS to existing power plants, would require more energy than that for just capture.

The cost of transporting the $CO_2$ to a suitable storage site needs to be added to it. For electricity generation the process is therefore unlikely to ever become cost effective in comparison with using renewable energy. Added to this is the time dimension. Building HVDC links involves rolling out well established technology. CCS is known to be technically possible, but not yet ready for commercial application. I argue that we need to phase out the use of fossil fuels urgently, and that this is done most cost effectively by a rapid build up of renewable energy supply capacity. That means that we need to face the reality that the use of fossil fuel is becoming an obsolete technology and the associated reserves will have to be written off. However, there is a growing expertise, which indicates that CCS could eventually also be used for removing $CO_2$ from the air. (Ferrari et al, 2014: 2).

Nevertheless Professor Myles Allen’s view (2013) is that it ought to be captured and stored. His key argument is (2013b) that: “We can't stop fossil fuels being burned”. In a world dominated by nation states and many countries and producers, he has a point.

In his *Daily Mail* article he also questioned the benefit of subsidizing a particular type of device to harvest renewable energy:

> “Subsidising wind turbines and cutting down on your own carbon footprint might mean we burn through the vast quantity of carbon contained in the planet’s fossil fuels a little slower. But it won’t make any difference if we burn it in the end.”

Here the second of these two sentences is crucial, whilst I beg to differ with the first point. Calling a halt to the burning of these vast reserves of fossil fuels is a *must*, both on account of the delay in getting CCS to work and because of the partial nature of capture. And it needs to happen as soon as possible. Subsidising renewable technologies, such as wind turbine installations is one way of getting the technology off the ground. Admittedly, assigning a cost to emissions via fuel extraction might be more effective than subsidizing renewable energy. However, the fact that the fossil fuel industry has a great deal of political clout, makes prompt implementation of this type of taxation according to the *Polluter Pays Principle* (Heesterman and Heesterman, 2013: 173*ff*. and references provided there), clearly a non-starter. And in any case, a period of adjustment, -temporization (*Ibid*: 180 ff) is essential.

In addition, there an issue of corrosion:

> "The corrosion rate in water saturated with $CO_2$ showed values between 1 and 28 mm/year." (Cabrini et al, 2014: 26 -conclusions-)

Not surprisingly, Professor Blunt (2010: 11) comments:

> "To avoid corrosion, the $CO_2$ has to be of high purity: in particular $H_2S$ and water need to be removed from the gas stream. In Europe, with high population densities, the pipes would be buried underground."

Clearly, these requirements make the processing and transport of $CO_2$ if directly captured from flue gases over longer distances a major cost item which comes on top of the cost of capture.

However, there is an alternative technology for capturing which appears not to present this particular drawback: It consists of making use of $CO_2$ from chimney stacks to grow algae and make an oil-like substance by biological processes. A plant based on that technology is now being built in New South Wales Australia (Newswire, 2013). The balance of my judgment is nevertheless that, whilst this technology may offer a suitable route towards capturing and storing $CO_2$ from the atmosphere, it is not cost effective for energy production, compared with using renewable forms of energy rather than fossil fuel in the first place. The cost of processing and transporting $CO_2$ as captured directly from flue gases can be largely bypassed if the geography is suitable for pumping captured $CO_2$ underground locally. This appears to be the case with the plant which was recently fitted with $CO_2$ capture near Esteven, Saskatchewan, Canada (MIT, 2015) However, it appears that the practicality of pumping the $CO_2$ straight down without removing the water vapour and sulphuric acid at Esteven is greatly facilitated by the fact that this place is at the centre of an oilfield (Government of Saskatchewan, 2015). The relatively low cost of the end disposal of captured $CO_2$ without further processing does not generalize to power stations not situated at such a suitable location. The use of the captured $CO_2$ to help oil recovery (MIT, 2015) obviously further reduces the cost.

There is, however, more to Professor Allen's proposal as reported above than what appears to have made the pages of either *The Daily Mail* or *The Guardian*. We attended his lecture at the Society of Chemical Industry (Allen, 2015c), in which he explained that fossil fuel producers should be required to capture and store a gradually increasing *fraction* of the $CO_2$ emissions implied by their extraction, which should climb to 100%. This procedure closely matches our reference to temporization (Heesterman and Heesterman, 2013: 151*ff*, 180*ff*).

I take it that Professor Allen's reference to certification includes the provision of independent proof that $CO_2$ is being captured and stored by some other organization. If so, his proposal comes near to what I outline below, except that in his version, a carbon tax with a possibility to offset is replaced by a requirement to sequester and store $CO_2$.

However, for the reasons outlined above CCS would in practice, under both his and our proposed scheme, mainly apply to sequestration from the air or from industrial processes other than power generation, such as cement making.

As long as the relevant fiscal agents consist of national governments, rather than a World Government which could pay for reduction of the $CO_2$ content of the atmosphere out of global taxation, payments by public authorities *to* companies or other types of organizations for removal are difficult to envisage. It could, however, conceivably be financed out of an arrangement to offset taxation on any remaining $CO_2$ emissions.

To stimulate research and development and eventual commercial application of CCS from the atmosphere, temporization of the introduction of a carbon price / emissions charge (Heesterman and Heesterman, 2013: 179-180) would mitigate its near-term socially disruptive consequences. The same consideration applies to Professor Miles' proposal to require a gradually climbing fraction of emissions to be captured and stored. The *benchmark price* is the price at which an alternative sustainable technology is known to become commercially viable, even if so far regarded too expensive to be commercially viable now (Heesterman and Heesterman, 2013: 179). This does not mean that the actual cost may ever reach the benchmark price: the very fact that emissions will carry a financial cost is bound to stimulate research and development as a result of which more cost effective technologies may be found.

If an emissions price is temporized, whilst it is scheduled to rise to a high level, end-users' continuing use of $CO_2$ generating processes could via the offset be a route to finance the removal of $CO_2$ from the air.

Thus, an airline might emit x tons of $CO_2$ by continuing to use fossil fuel derived aviation kerosene, and would pay for the capture and end-storage of, let us say, of one and a half x tons of $CO_2$, i.e. paying for the removal of one and a half times its emissions. This type ore re-burial of carbon would not necessarily have to be in the form of $CO_2$. The solid form as mentioned by Licht and Ren (2015) above might be more straightforward to transport and/or bury locally. The benchmark price for emissions (Heesterman and Heesterman, 2013: 179) could then be set either at a cost estimate based on an already existing pilot product to make synthetic fuel from carbon dioxide, water and energy, or at a cost estimate derived from a pilot project for CCS from flue gases, whichever the higher. Remaining emissions from 'cleaned up' flue gases would remain taxed, but could also be offset. If a cement factory emits y tons of $CO_2$, even after CCS and is charged accordingly, this could be offset by paying for the removal of 1.5 y tons of $CO_2$ from the air by some other organization. If so, one of two things is bound to happen. Either synthetic fuel will be used without any net emissions at all (at least for aviation), or any remaining emissions would become a source of net reduction of the $CO_2$ content of the atmosphere. Note that whilst the actual cost of flying or of cement production is likely to increase as the emissions price moves up towards the benchmark price, in Professor Allen's version of the scheme the charged price could also come down again, when the cost of removing $CO_2$ from the air becomes less.

The incentives on technological development are similar in the case of Professor Allen's scheme and the one outlined above. Both schemes also require the support of additional import duties on "virtual emissions" from products made in countries not participating in the scheme (Heesterman and Heesterman, 190), whilst Hansen (2009) refers to the same provision as 'border taxes'. Such a provision not only avoids that domestic producers have to face the competition of under-costed imports from non-participating countries. It also means that once a reasonable number of countries join the scheme, initially non-participating countries come under pressure to join as well, to avoid their exports being surcharged.

However, the income distribution implications of the two schemes are not equal. On that point, I stick to my opinion, that in the absence of global taxation, an agreed rate of national eco-taxation, with a share of the implied rental value of the composition of the atmosphere being handed over to a suitable United Nations fund (Heesterman and Heesterman, 213: 189) is preferable.

Roberts (2014) argues that a third pillar of the United Nations Framework Convention on Climate Change (UNFCCC) should be a mechanism to manage the adaptation to climate change, as in principle agreed in Doha (UNFCCC, 2013), subject to clarification of the details. I have no doubt that this would be desirable, for its own sake as well as to ensure the political support for serious action on climate change. A provision for the UN to be allocated a share of emissions related eco-taxation would be an obvious source of funding to make this a reality, while avoiding serious concern about a potential open ended commitment for compensation of climate change damage. In fact, the US has subsequently indicated that it is opposed to any such "third pillar" arrangement (Sethi, 2013), and the fear of demands for substantial sums of compensation may well have been a main reason for that.

# Conclusion

We should no longer delay replacing the use of fossil fuels by renewable energy. CCS is needed both for the removal of $CO_2$ generated by processes other than power generation and for bringing back the $CO_2$ content of the atmosphere to a more sustainable level, but we should not wait for the renewables technology to mature any further. Instead, we should proceed rapidly with the replacement of the use of fossil fuels by renewable energy. The financial and social consequences of the resulting redundancy of known fossil fuel reserves and of installations dependent on their use, will then need to be faced.

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