Clean Techn Environ Policy (2017) 19:295–310
DOI 10.1007/s10098-016-1277-x

PERSPECTIVE

The pace and practicality of decarbonization

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Received: 7 April 2016 / Accepted: 6 September 2016 / Published online: 26 September 2016

Abstract There is a widely believed myth that replacing the use of fossil fuels largely by renewable forms of energy is, with a possible exception of nuclear power, critically dependent on the development of appropriate new technologies. Accordingly, it is held that decarbonizing straight away is particularly difficult and expensive. 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 presumed 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 fuels via hydrogen obtained by electrolysis of water and CO_2 integrates smoothly with electricity grid stabilization as well as reducing the CO_2 content of the atmosphere. The likely price and cost development in the energy market is also reviewed. In addition 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 · HVDC technology · Synthetic hydrocarbons · Transport fuel · Ocean acidification · CCS · CCU

The myth

The following quotes may serve to show 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)
> […] new nuclear is the only proven low-carbon technology that can provide continuous power, irrespective of whether the wind is blowing or the sun is shining. (Rudd 2016)

The reality

These views depend on incomplete and outdated information and are no longer supported by the facts, as is clear from the documentation below. Newer, more effective methods are always welcome, but there are reasonably cost-effective technologies around which can be used to rapidly replace fossil fuels by renewable energy.

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The issue has been covered earlier by other authors, such as Neven Duić (2015), a researcher from Croatia bringing us a perspective other than those of the Anglo-Saxon part of the world, which tend to dominate publishing in the Western world.

Unlike the authors mentioned in the "The Myth" section above, Duić acknowledges that: "clean energy systems based on renewables are technically and economically feasible". Whether we have already reached "the point of no return" within the limits of the technologies discussed by Duić, and whether full decarbonization can only be reached by 2050 as Duić has it, is another matter.

Some details regarding the technical and factual information as well as economic theory which Duić ignores or which he mentions somewhat cursorily are summarized lower down. I submit they are quite relevant and greatly increase the chances of a rapid transition.

Additionally, I have certain reservations concerning the mechanisms which lead towards the conclusions: There are two main areas, which need discussing. These relate to who and what drives the transition, and the available technologies.

State and non-state actors

Ascribing the hoped-for outcome to the resolve of governments ("Spearheaded by government policies"), omits the fact that effective change is seldom initiated without a certain pressure from below. Indeed, if it were not for such pressure from below on governments, the outlook might be bleak, as the vested interests to which Duić rightly refers to in his final concluding section have significant lobbying power over governments and political parties. This can include the promotion of disinformation (Heesterman 2015). In addition, there is a danger that a general tendency to inertia and keep to known and tested processes, despite a potential repressed understanding that climate change is a risk to one's future and that of one's descendants, half truths may well be accepted by many, including policy makers, leading to prolonging the status quo. Action to overcome this kind of passive resistance requires dedication. Certainly, involvement by business, leading to support by market signals, is of the essence.

Targets for renewables—and not to forget the effective mechanisms for implementation—are stronger in certain countries (or states) than others: Austria set a target for 45 % of all energy to be from renewable sources by 2020 (REN21: 161); the UK regional government aims to have electric power generation to be 100 % renewable by 2020 (Ibid: 167).

These possibly come in the category of being according to government policies. In other instances, pressure from concerned citizens, NGOs and/or business coalitions has been decisive. An example is the court case that led to strengthening of the target of the Netherlands from at most 17 to 25 % (Lambrecht and Ituare 2015). A notable exception to the need for pressure from civil action is the policy declaration of Saudi Arabia's oil minister Al-Naimi, who stunned his audience at the Business and Climate Conference in Paris by proclaiming that fossil fuels would be unnecessary in Saudi Arabia before the middle of this century. Instead, he argued that the country would be moving into solar and wind power (Moors 2015).

A further confirmation that Saudi Arabia is indeed preparing for a post-oil economy is the invitation to Jeremy Leggett to write an article in the country's national finance daily *Al Eqtissaih*. I take it that an article opening with the passage:

> In 2016, the Kingdom of Saudi Arabia has a major opportunity to develop a new industry, an opportunity that became something of an imperative in 2015. Let me examine first the opportunity, then the imperative. The opportunity involves solar energy, which is fast heading towards becoming the cheapest unsubsidised form of energy on the planet (Leggett 2016: 2).

would not have appeared in the journal in question without a degree of official approval.

It appears Saudi Arabia intends to pursue a policy by deliberately depressing the current oil price, in order to suppress the more costly (and emission-producing) technology of fracking, extolled in the USA as a source of cheap gas (Mourdoukoutos 2016).

A nation that is a prominent oil exporter appears to be switching to the export of electricity. On this point, Duić's statement:

> critical excess electricity production, CEEP […] is not exportable (p. 2098)

is at variance with the known facts. Saudi Arabia clearly intends to rely on the HVDC technology, to be discussed further down.

This brings us to the issue of directly usable ("exergy") and excess electricity production, which Duić seems to regard as of little use.

The technology and economics of electricity distribution

The goeographical and physics constraints on electricity distribution

There are two main reasons why long distance transport of energy greatly facilitates the reliable supply of renewable energy at the time and place where it is needed. One is that the geographical locations where renewable energy is most suitably harvested or stored is quite uneven and if anything tends to be concentrated in thinly populated areas.

Some obvious examples are:

(a) Hydropower and pumped storage concentrate on high mountains, both because mountains attract rain, and because it is easy to find suitable spaces for an upper and a lower reservoir with a great difference in elevation. In that case, the turbines at the lower reservoir double up as pumps that can, when there is excess supply of power available, pump water from the lower reservoir back into the upper reservoir. See also Energiewende (2016). Whilst this reference has a general European context and also refers to the pumped storage potential of the Alps, storage of the nightly excess supply of wind power from the Baltic and North Sea offshore areas of Germany and Denmark as pumped storage in Norway is well underway. Norway hopes to utilize its geography, which is particularly suitable for the development of pumped storage systems to become "Europe's battery" (Phys Org 2015a). There are now no less than four HVDC cables below what is basically the same stretch of water, the Skagerrak, the sea passage between Norway and Denmark (Fairley 2014). A refinement of the hydroelectric technology as now increasingly used in Norway is the use of tunnels rather than pipelines between the upper and lower reservoirs. These tunnels are not as visible as pipelines and often contain a "surge chamber", a cavern inside the mountain near the power station. These can, via their ventilation tunnel, accommodate sudden changes in water pressure to a much higher level in order to facilitate rapid start-up and shut-down of the turbines (Phys Org 2015a).

Some countries have the good luck of having the conditions suitable for harvesting renewable forms of energy and pumped storage independent of rain and fresh water supply close to each other. A pumped storage system using the Pacific Ocean as the lower reservoir, with the upper reservoir high up in the Andean mountains, has been built in the Atacama desert in Chile. (Phys Org 2015b; Jarroud 2016):

(b) The other obvious example of where there is plenty of energy to harvest, but few inhabitants is a desert where the sun is rarely obscured by cloud cover.

(c) The suitability to harvest wind power is in practice much greater in coastal areas than inland. Investment in wind power in Northern Germany has risen sharply in particular offshore, in the Baltic and increasingly in the North Sea (Federal Ministry of Economic Affairs and Energy 2015). The obvious result of this development is an excess of supply of electric power where the wind is, i.e. in Northern Germany, whereas demand outstrips generation in Southern Germany. To cope with this situation, two North–South HVDC links are planned. Of these, the route of one has already been decided: It will be between a site near the Dutch/German border on the North Sea coast, and Phillipsburg, some 70 km north of Stuttgart in Southern Germany (Fairley 2013). There is also a discussion of fitting this HVDC connection with interrupt switches capable of stopping the current in milliseconds. If these superfast switches do indeed work correctly then IEA-REDT's (2013) fear that they might fail in the field can be laid to rest. In that case, it would become practical to build offshore wind farms in the Dutch sector of the North Sea and have the energy transferred to the German HVDC link and to AC further South. Use of this energy in the Southern part of the Netherlands and in Belgium, would then not be endangered if something went wrong even further South in Germany.

The second main reason why long distance transport of energy is useful is that the variability of the weather manifests itself predominantly locally: The possibility to import energy from where it is naturally available to be harvested at a particular time greatly increases the reliability of supply.

DC versus AC

As to the physics, two points need to be borne in mind: First of all, the energy loss due to the conversion of electric energy into heat in a connecting cable is proportional to the amperage, whereas the energy transmitted by a cable is the product of the voltage and the amperage. Hence this form of energy loss is reduced by using high voltages. Secondly, any electric current generates a magnetic field, whereas a change in the strength of a magnetic field generates a current. This is the basis of the magnetic induction transformer, which can change the voltage of alternating current which changes direction 50 or 60 times per second. This is a widely used device, which is able to transform a current of a relatively low voltage into a higher one for transmission with relatively little conversion of energy into heat in the wire, or the other way round in a substation, to a voltage that is reasonably safe in a home or office. Its existence is the reason why AC was opted for in the first place (Wikipedia 2016d; Inside Energy 2015).

What is now rapidly becoming standard is a three layered system. There are two levels of AC current transmission. Over distances of perhaps a few hundreds of kilometres, there is high voltage AC, at perhaps 10,000 or 20,000 Volt, typically using cables hanging on pylons. Even so, this system of transmission still incurs significant losses. There are, however, problems with simply using even higher AC voltages. For one thing, the steel poles carrying the cables can act as transformers. The alternation of the direction of AC current in the cables generates an alternating magnetic field and causes secondary currents in the poles. The other problem is that air, and especially moist or dirty air is not the perfect insulator one might like to think it to be. This type of power leakage is known as the *Corona effect* (Parmar 2011).

Transfer of large amounts of energy in the form of high voltage AC in properly insulated cables runs, however, into a different problem: The local electric tension field between the metal cable and the insulation material has to be adjusted 50 or 60 times per second and which also costs energy. These problems are circumvented by using High Voltage Direct Current (HVDC) for distances of more than a few hundreds of kilometres.

I found no reference to the HVDC technology in Duić's article whatsoever, and it is making a crucial contribution towards ensuring reliable supply of locally intermittent renewable forms of energy. High Voltage Direct Current (HVDC) cables are now used to transport energy in the form of electric current over thousands of kilometres. As indicated earlier, 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 continues to be applied on a massive scale with fossil fuels transported in bulk by CO_2 generating transport, such as tankers or bulk carriers loaded with coal. The alternative method of transporting renewable forms of energy (in practice electric power in particular) is by means of a HVDC cable connection.

Whilst the conversion between AC and DC causes a certain energy loss and requires costly facilities, a HVDC link is nevertheless advantageous for a large offshore wind farm with a capacity of 500 MW or more and a distance from the high voltage AC grid on the land of 200 km or more. (Elliott et al. 2015).

The advantages of long distance transport of electricity via the HVDC technology and its integration with regional AC grids may be summarized as follows:

(1) 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 and used in more temperate zones as well as geothermal energy in volcanic areas, wind where it is reliable available, such as on shallow sea areas and in the subtropical areas, where the trade wind is much more stable than it is in the temperate climate zone, and used where required.

(2) Pooling of resources: Supply across time zones reduces the maximum capacity needed to meet peak demand.

(3) 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, whilst demand may be met by energy import in case of insufficient local supply.

I have, however, been surprised to note that the use of thoroughly insulated cables so far appears to be the exception, the usual practice being mounting them on pylons without the weight of hefty insulation, using impregnated paper as insulation (Chen et al. 2015: 11): a search for the string "underground" in a list of ongoing electricity infrastructure projects published by the European Commission (2016) produced only a few hits for underground HVDC links. However, the German government is now insisting that underground should be the norm (Recharge 2015). Recharge cites public perception as the reason, but that perception could be well founded. HVDC connections nowadays use quite high voltages: That is what contains transmission loss specifically for DC. What would happen when there is a severe storm or freezing rain? Or a suicidal aircraft pilot flying into it? However, once the cables are safely underground and properly insulated, the problem of their visual impact also disappears.

I am, therefore, rather sceptic regarding Duić's conclusion on p. 2096:

> [..] which will enable that residential installations are slowly converted from alternating to direct current, the type of electricity that is actually mostly used in homes, reducing the conversion losses.

Most domestic DC appliances (not washing machines, refrigerators, air conditioning installations, lawnmowers, electric heaters and cookers, which so far are generally use AC) use a variety of significantly lower voltages than the 220 Volt (or 110 or thereabouts in most of the Americas) which is now the usual domestic AC voltage. Transmission even over a distance of say, a couple of kilometres from a local substation to people's homes at, for example, the 3 Volt as used by the controller of our TV would result in an unacceptable degree of energy loss. They therefore need either batteries or else transformers as well as rectifiers.

Some information about the economics of HVDC transmission

Duić's emphasis on local generation is too strong. I would go as far as to suggest that the concept of CRES—Critical Excess Electricity Production—has little relevance in the light of the available technologies; contrary to what he states on p. 2098, it is exportable. Some information on the economics of the generation of wind power on the Baltic coast of Germany, whilst storing the surplus of wind power supplied during the night via pumped storage in Norway is useful at this point.

The transmission loss in an 800,000 Volt 2000 km long High Voltage Direct Current (HVDC) link is about 5 % (ABB, undated). The distance from the Baltic coast of Germany to central Norway is only about 1000 km; hence, 5 % total transmission loss is not unreasonable. Conversion losses need adding; these are about 3 % at most—Siemens (2013) quotes this figure as the total loss for transmission of a couple of hundreds of kilometres.

To that come some 15 to 25 % energy losses in the pumped storage operation itself (RP Energie Lexicon 2016).

The dominant capital cost item is the HVDC link, typically about 1000 Euro per KW. The actual cost of the pumped storage operation are about 5 Eurocent per KWh. Typical electricity prices in Europe were in 2014 about 20 Eurocent per KWh, about half of which were actually taxes. (Eurostat 2016)

These figures mean that exporting the surplus of wind power during the night gets about 60 % back as energy supply during the day. That loss is less than trivial, and the alternative of local use is certainly worth evaluating—but not at almost any cost.

Note also that investment in wind power in Northern Germany has risen sharply and in particular offshore, in the Baltic and increasingly in the North Sea (Federal Ministry of Economic Affairs and Energy 2015).

The obvious result of this development is an excess of supply of electric power where the wind is, i.e. in Northern Germany, whereas demand outstrips generation in Southern Germany. To cope with this situation, two North–South HVDC links are planned. Of these, the route of one has already been decided: It will be between a site near the Dutch/German border on the North Sea coast, and Phillipsburg, some 70 km north of Stuttgart in Southern Germany (Fairley 2013). Note also the discussion above concerning fitting this link with superfast interrupt switches, whish, if working correctly in the field would make it safe to use it to transport power from the Dutch sector of the North Sea to Belgim and the Southern part of the Netherlands.

It must happen, via the market or otherwise

In relation to the title of Duić's article: "Is the success of clean energy guaranteed?"—with a question mark, there is the issue of what might be the alternative. Unlike Younger et al. cited above, Duić is not suggesting that replacing fossil fuels by renewables is technically impossible. On the contrary, he clearly states in his introduction, that it is technically possible even where it is most difficult, on the restricted space of an island. I take the question "Is the success of clean energy guaranteed?" to mean that, perhaps, an adequate and timely level of replacement of fossil fuels by renewables may not happen under market economy conditions.

If so, there is the possibility of a more command type of economic management and the issue whether we should in view of the cost of decarbonization, accept that catastrophic climate change should not be an issue. There are three time dimensions of that issue of catastrophic climate change.

One is that there are already signs that climate change is running out of control with global warming starting to feed on itself.

In the end of April and beginning of May 2016, there was a heat wave in Alberta, Canada, with the temperature in Southern Alberta reaching 34 °C (CBC News 2016) whilst further North in the less densely populated and more forested part of the state, huge swathes of forest were tinder dry and laid to ash (Graney 2016). I, nor CBS News and the scientist to which it referred believe that this is part of normal weather variation. Nor do I believe that the forest should have been so dry so soon after what normally is in that part of the world the main spring snowmelt. Maintaining normality in that sort of heat implies a huge increase in the demand for power for air conditioning. As does the 51.6 °C in Kuwait, Western Saudi Arabia and Southern Iraq, which is in line with climate model forecasts (Pal and Eltahir 2015), and which now appear to have become observed in reality (Freedman 2016). That increase in demand for energy to run air conditioning is now almost certainly the only way normal human life in the anthropocene can be maintained. That energy supply for airconditioning has to come from renewable sources, via market mechanisms or otherwise. Heat-wave-driven forest fires (and not just in Alberta) also are a huge source of emissions.

The second time dimension is what kind of future earth the living generation will be leaving to that of their children and grandchildren. This one is usually framed in terms of a set target ton ensure that global warming is limited to a specific figure, e.g. the 2° target agreed in Copenhagen, or the 1.5° target agreed in Paris. We now know that a 2°

warmer world is already one which is likely to have some quite unpleasant characteristics.

Hansen et al. (2015) report evidence of superstorms during the previous interglacial, the Eemian (also known as marine isotope stage 5e), when the earth was warmer, but most definitely not by more than 2 full degrees Centigrade above Holocene levels:

> [….] wave runup deposits that reach heights nearly 40 m 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 et al. put 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 boulder more than 30 metres high up the beach. These authors also reckon that IPCC's estimate of sea level rise by the end of this century could be an under-estimate. Note also that, whilst the Hansen et al. evidence of the speed of sea level rise during the Eemian is complicated by the absence of Carbon 14 dates for more than about 40,000 years ago there is also evidence of fast sea level rise in much more recent times. It crucially rests on the fact that around 14,000 years ago the growth of coral reefs was unable to keep up with sea level rise, a sustained speed of sea level rise of on average about 4-cm per year (14 metres in about 350 years), which *was* confirmed by Carbon 14 dates (Gregoire et al. 2012).

What makes it worse is that, although carbonic acid is a weak acid, its sheer massive amount under business as usual is likely to imply a complete collapse of marine ecosystems (Caldeira 2011: 99). Question: What will happen, if, despite a modest degree of replacement of fossil fuels by renewables, the total amount of emissions continues to rise, due to both increased demand for air conditioning and as a consequence of increasing forest fires?

The third time dimension is what will happen eventually. The current *level* of the earth's greenhouse gas burden is unsustainable. The greenhouse effect has caused the energy leaving the earth as infrared heat radiation to drop below that of the Sun's incoming rays. The warming of the land may be more noticeable, but because waves and currents mix the ocean's water, so far most of the difference is absorbed by the enormous thermal mass of the oceans. (Katz 2015) This circumstance means that, irrespective of timing, reducing emissions is insufficient by itself. There is a need for technologies capable removing CO_2 from the atmosphere. Here the happy coincidence arises that, whereas CCS (capture and storage of CO_2 from chimneys) is an expensive add-on to the fossil fuel technology, the manufacture of synthetic fuels from CO_2 and energy via the production of hydrogen by electrolysis of water is a reasonably well-known technology, which also allows negative emissions by pumping synthetic hydrocarbons back into oilfields.

The relevant economic theory

There is an issue as to whether it is a given self-evident that once a particular type of energy infrastructure is in place, it should be kept operative until the end of its technical life span. In that context Duić (p 2094) and the International Energy Agency to which he rightly refers use the term "locked in". The expression implicitly assumes that equipment is necessarily kept running until the end of its technical life. This does not take the economic concept of obsolescence into account. If further use of a particular installation is no longer profitable, it should be taken out of service as being obsolete. There are two main ways in which this tends to occur. Newer more effective technologies may become available, and materials and other resources used may become more costly. Whilst I commented above on the choice between opting for a centrally planned command type of economic management versus accepting catastrophic climate change, the economic viability of continuing to use fossil fuels is in fact shaped by rather less drastic deviations from the completely free market economy than abolishing it. This applies in particular to assigning a cost to emissions.

Pigou (1920:161-162) argues that in view of the cost which alcohol misuse inflicts on society: "the industry should be debited for the indirect cost of policemen and prisons". And most governments have taken his recommendation on board and charge duties on alcoholic beverages, indirect taxes above any general rate. The generalization of Pigou's argument to "fossil fuel producers should be debited for the indirect cost of climate change" is straightforward. For administrative reasons, the practical way to implement a tax of this nature is not an emission tax which would require monitoring equipment on every chimney and exhaust, but a carbon tax, a duty on fossil fuel extraction.

It is debatable whether and to what extent carbon taxes are politically expedient and indispensable to sustain the momentum of the renewable industry. Although indirect taxation is according to economic theory the best way to maximize society's utility, in my view measures to support the renewables industry will attract less opposition from fossil fuel companies, than taxation on fossil fuel extraction would.

Duić does not in any explicit way deny the existence of obsolescence. However, the invocation of the reference to Priya and Santanu (2013) in the passage

> Traditionally, technologies are compared on investment costs or levelised cost of electricity (Priya and Santanu 2013), which will generally prioritize old technologies, due to lock in effect and the fact that VRES are capital intensive with upfront cost.

appears to come close to disregarding the occurrence of obsolescence.

Priya and Santanu (2013: 777. Table 3) give the life time of a coal fired installation as 40 years, quite irrespective of any emission charge or falling cost of electricity. What puts this last point into particularly sharp focus is the sharp and consistent reduction in the cost of solar panels. Although the main text of Priya and Santanu gives the date of their source reference to Nouni; Mullick and Kandpal as 2012, verification of Priya and Santanu's list of references indicates that this was the time they downloaded the article, whilst the publication date was 2008. Between 2008 and 2012, the cost of photovoltaic panels has roughly halved (Feldman et al. 2012: vi, graph). In addition, Farmer and Lafond (2016) argue that for any given technology, there is (conform Moores Law) a reduction in its cost, which is fairly stable over time for a specific technology. They investigated photovoltaic solar power as one of 53 technologies, finding an annual cost reduction of approximately 10 % in the case of this particular one. Regardless of the general validity of Moores Law, we may reasonably expect that mass production will result in further reduction in the cost of photovoltaic electricity. The idea that coal fired power will not be obsolete earlier than in 40 years time is less than entirely credible.

Up to a point, Duić takes his distance from this implied denial of obsolescence: Further down the same page he pleads for calculating costs on the basis of "market feasible number of hours". That does raise the question whether this number of hours might be equal to zero. Once that point is taken, we have no locked in problem, but instead have to face the financial consequences of stranded assets.

In any case, regardless of the route by which this is accomplished the balance of my judgment is that the fact that the use of fossil fuels is an obsolete technology is a reality which needs to be faced. Alternative technologies are available, whilst continuing the use of fossil fuels will ruin the planet.

It is also the case that many fossil fuel producing companies are by conventional standards "too big to fail": The option of a gradual smooth transition under normal market economic conditions might have been on the table if the problem had been taken as seriously as it should have been at Copenhagen in 2009.

The other issue to be mentioned here is the social costs of insolvencies and their effect on economic growth. In his introduction, Duić argues that insolvencies are a social cost and are likely to reduce economic growth. Here my position is the Keynesian one. Yes, there is a major adjustment problem, but the feasibility of any particular rate of growth depends on the availability of real resources, and if the financial sums don't add up, then it is the task of public authorities to intervene with suitable correcting measures. Stimulating investment in objectively useful installations such as those that harvest renewable forms of energy is one way to do so. I shall come back to that issue further down.

The available technologies

If one takes the range of technologies and their capabilities surveyed by Duić as the last word, then I fear that, if we leave the change-over from fossil fuels to renewables entirely to market processes without any public intervention the short answer is that society is heading for a climate change catastrophe.

I do not, however, think we have quite come to having to make the choice of abolishing the market economy or facing catastrophic climate change. There are major technological innovations dating from the last decennia and even before that, which Duić does not mention.

Yes, there is a problem of the supply of renewable energy being intermittent. However, recent years have seen a major research effort to improve battery storage, and it begins to show results. There now is a range of suppliers who offer various types of batteries to enable you to normally enjoy 24-h reliable electricity supply from solar panels on your own roof. They range from batteries using sea salt and carbon electrodes (Dr Ten 2015), lead acid batteries which are basically improved assemblies of components similar to those of car batteries (Powervault 2015), to sodium sulphate batteries (Aquion Energy 2013), and lithium ones which are not too dissimilar from those used in electric cars (Tesla Motors 2015). All of these now assume that if there is a succession of cloudy or misty days in which there is very little power from one's roof, you can clearly fall back on external power supply via the grid. But, given that the weight of the battery is of limited relevance for this purpose, surely they could be scaled up to a level where they could bridge a longer period of non-supply of sunshine or wind power. In a global and large scale regional setting, there are other technological avenues.

There are several statements of fact in Duić (2015: 2906) with which I beg to differ. It is perfectly true that we cannot at this moment realistically evaluate wave or ocean thermal power, because no adequate information about their potential "technological readiness" is available due to the lack of successfully operating pilot projects.

The same is, however, not applicable for tidal and geothermal power. There are in any meaningful sense, two versions of tidal power, the large scale one involving a dam in an area of a substantial difference between high and low tide such as an estuary, and placing turbines in sea straits with a strong tidal current without any dam: *tidal current technology*. There are some fierce tidal currents between islands and larger masses of land, as well as in the openings of sea lochs, or to use the Norwegian rather than the Scottish word, fjords. A tidal power station with a reservoir-type dam has been operational since 1967 in France (de Laleu 2009), and one in the UK is planned for the Swansea Bay in the Firth of Severn (Macalister 2014). A 65 Kw facility of the small scale tidal current variety has been operational at the Race Rocks ecological station near Victoria, British Columbia, Canada since 2006 (Whiticar 2012). No less than 89 sites suitable for similar turbines were identified in this region (Clean Energy BC 2015). I have myself seen the installation of a turbine in a sea passage off the West coast of Scotland. Some obvious advantages of the tidal current technology over the dam and reservoir-based one tare its smaller impact on the local marine environment, its very much smaller lead time, and the fact that in a country of any size with an adequate capability to transmit electric power from one end of the country to another, it provides predictable round-the-clock power supply without requiring too much energy storage.

As to geothermal power, there are other references which clearly indicate that there is a substantial geothermal energy potential.

> Geothermal Energy Could Provide All the Energy the World Will Ever Need (Renewable Energy World 2010).

There is, however, no realistic prospect of any soon realization of a full scale switch to geothermal only: A check on the sources cited for this contention indicates that this relates to drilling as deep as 10 km into the earth (Renewable Energy Focus 2010). There is nevertheless a significant potential for geothermal energy supply, which is more readily available in certain parts of the world.

There are volcanoes in the so-called Ring of Fire around the Pacific Ocean, on the Northern side of the Mediterranean, on Iceland and in the Rift Valley in East Africa. Thus, Think Geoenergy (2015) lists the USA, the Philippines, New Zealand, Indonesia, Mexico, and Japan (all in the Pacific Ring of Fire), as well as Italy and Turkey (Mediterranean) and Kenya (East African Rift Valley) and Iceland as having significant amounts of installed geothermal power capacity. Of these countries, Indonesia has many volcanoes: It is a relatively densely populated country, because the fertility of its soil is regularly replenished by volcanic ash. We may reasonably assume this country to have a substantial potential to export geothermal energy. The same applies to Iceland, which is therefore looking forward to the possibility to export its surplus of geothermal energy to Europe, via an undersea HVDC link (Landsvirkjun 2016).

Duić (2015: 2094) also mentions heat pumps. I note in that context mention that whilst this is doubtless a source of energy, the one supplier of ground source heat pumps which I was able to identify (Mitsubishi Electric 2016) in effect supplies a reverse fridge, transferring heat from the ground into your house, using, as with ordinary fridges, a HCFC containing substance as transmission medium. As HCFCs are strong greenhouse gases in their own right, I am sceptical about this idea, even whilst this substance is not supposed to escape into the atmosphere.

In relation to Indonesia's probable potential to export geothermal energy (and other potential energy sources), it is useful to mention a technology which is crucial to overcoming the intermittence problem in the context of a wider geographical area; the High Voltage Direct Current technology, to which I found no reference in Duić's article. On the contrary, Duić (2096) seems to assume that the future is one in which "stationary power by then would already be decentralized". Yes, it is the case that photovoltaic solar panels on roofs allow a fair degree of decentralized power production. Nevertheless, I reckon the generation of power in larger production units cannot be dispensed of, quite irrespective of whether and when fusion power becomes operative. There is another technology to which I found no reference in Duić's article which has the same scale economies as fossil fuel-fired power stations and which also is at it most effective in a hot desert climate. This is *Concentrating Solar Power* (CSP). This technology uses a computer-controlled array of mirrors, to concentrate the sunshine either directly on a steam boiler, or on a reservoir containing a substance (usually a mixture of molten salts) to buffer the heat of the sun over time and to transport it to the boiler. Strictly, the proper name of this technology should be Concentrating Solar Thermal Power: The same arrangement can also be (and is) used to concentrate the sunlight on PV panels, but the name Concentrating Solar Power has become usual. The boiler itself is basically the same as used in a fossil fuel-fired power station (National Renewable Energy Laboratory 2015). The omission of any reference to CSP in Duić's article is the more remarkable because he does mention an in practice closely related technology, heat storage in a domestic supply context, whilst pleading for creating a market for heat. However, whereas measuring the supply of domestic gas or electric power to a home or office is straightforward, the supply of heat is not easily measurable and preserving the energy for its end user requires additional investment in well-insulated pipes. The difficulty in measuring the effective supply is a serious obstacle against organizing a market in heat supply. The most practical heat storage medium besides hot water is molten salt, and that is what is commonly used to enable a CSP power station to supply power during the night, without any metering and charging problem for the heat. It is therefore more practical to combine the heat storage with CSP and use electric heating (Kraemer 2016).

Synthetic Hydrocarbon Fuels

This is an issue at which Duić (p. 2099) hints at as a possibility in the distant future. In fact the technology is reasonably well known, but was not commercially attractive as long as cheap fossil hydrocarbons were available. It is at this point useful to mention that, whereas electric cars will do fine in daily city use, the weight of the battery gives rise to a range restriction, as may be illustrated in Table 1 below, by comparing the energy content to weight ratios of a fossil fuel with that of the usual type of battery for motor vehicles. Salt batteries have even lower energy to weight ratios and are clearly not usable as car batteries.

These figures suggest a ratio between the energy intensity of fossil fuel and the lithium battery of more than 30 to 1. However, this ratio is distorted by the poor efficiency of the internal combustion engine and the several hundred kilos weight of its cast iron engine block. Nevertheless, it is clear that synthetic fuel would overcome a range restriction which does not apply to the electric car.

The Fischer–Tropsch process to make synthetic carbohydrates was developed in 1925 by Franz Fischer and his assistant Hans Tropsch. In 1934, it was applied on a manufacturing scale by the RuhrChenie corporation. Its original German form was a polymerization of a mixture of carbon monoxide and hydrogen obtained by heating coal suspended in water. The polymerization takes place at temperatures between 200 and 350 °C and uses iron or cobalt as catalyst to make petroleum like substances. The reaction was historically important during World War II, because liquid fuels could be made from domestically available coal. It was also applied in apartheid South Africa, to get round sanctions on the import of oil. Research on the process was resumed in the 1980s in the wake of the oil crises, but discontinued when the oil price dropped below $20 per barrel (German chemistry information service 2016). See also Wikipedia (2016a) and Stranges (2001).

There are several more recent procedures to make synthetic hydrocarbons using hydrogen and carbon dioxide rather than carbon monoxide as basic feedstock. Two of those are not too dissimilar from the original Fischer–Tropsch process.

There is first of all the Power to Gas (P2G) technology. This technology means that Duić's statement

> [..] using gas for heating houses is thermodynamically undesirable. (p.2094)

is out of date, because "gas" can be a renewable form of energy.

It is also the case that the modern gas-fired combination boiler which provides hot water for the tap as well as for the radiator, is an extremely efficient piece of equipment, typically with a thermal efficiency >90 % (Home Heating Guide 2016). Thus, even whilst we must eventually get away from the use of (fossil) natural gas altogether, the modern combi boiler is preferable over Combined Heat and Power, with its heat loss between the power station and the end use.

A facility for grid stabilization by storing energy in the form of hydrogen by electrolysis of water is now operational near Mainz in Germany (Energiepark Mainz 2015; CEE 2015). The hydrogen may then be combined with CO_2 to produce methane, which can be fed into the gas grid (Hampton 2013).

The use of spare capacity of wind turbines and other equipment to harvest renewable forms of energy at times when their electricity supply exceeds local demand means that producing hydrogen incurs essentially no cost, except of course the loss of any opportunity to use or store the energy elsewhere. Nevertheless this is an important qualification of Duić's contention on p. 2089 that there is a practical limit of 20 % on VRES (Variable Renewable Energy Sources) until the issues of energy transport or alternative use have been resolved: These issues have been resolved, even though it will for some time remain a problem, until sufficient capacity to balance temporary supply an demand imbalances by electrolysis of water has been built—but not at 20 %—given the availability of HVDC.

The primary form of gas produced by electrolysis of water is hydrogen (plus oxygen). This can then be used to process carbon dioxide and hydrogen into methane and steam. This reaction involves heating a mixture of CO_2 (carbon dioxide) and hydrogen to app. 300–400 °C and a nickel catalyst.

Table 1 Comparison of energy storage versus weight

Power supply source	Energy intensity in watt hour per kg	Reference
Kerosene	12,200	TRBP 2015
Lithium battery	400	Cleantech 2015

CO_2	+	$4H_2$	→	CH_4	+	$2H_2O$	+	energy
Carbondioxide	+	hydrogen	→	methane	+	water vapour		

It is known as the *Sabatier* reaction (Wikipedia 2016b), after the French chemist Paul Sabatier (1854-1941) and actually *produces* some heat. See also Wisniak (2005), which gives the source references to Sabatier. Clearly at least a part of the hydrogen generated at the Mainz plant could in the future be used to produce methane for the gas grid or for further processing. However, to get the Sabatier reaction going requires heating a mixture of carbon dioxide and steam in the presence of a nickel catalyst to some 300–400 °C, and recovering this initial heat as well as the additionally generated heat is not straightforward: If the superheated steam is separated from the methane by cooling to water, the energy is lost to the coolant. Siemens (2016a) reckons that conversion of hydrogen into methane actually costs energy and argues that hydrogen should itself be used as fuel wherever practicable.

Nevertheless, one obvious advantage of the conversion of hydrogen (and carbon dioxide) into methane is that methane is chemically identical to the main component of natural gas and can therefore be transported and used in the existing gas grid and gas-fired appliances.

I now come to discuss transport fuel. Direct use of electricity generated by sustainable methods has an obvious role to play. However, electric battery powered cars have a range restriction, as no battery can beat the energy content to weight ratio of carbohydrate fuels, and in any case there is the knotty problem of maritime and air transport.

Dujić only refers to the processing of hydrogen and CO_2 into liquid carbohydrate fuels, as something which may develop only in the distant future.

> In that case, a solution may still have to be chemical fuel made from excess electricity, more probably synthetic hydrocarbons than hydrogen, […] (p. 2099)

Such technologies are already available. There is first of all further processing of methane. Because methane is a gas, its storage or transport as a liquid requires facilities to keep it at very low temperatures and/or high pressures. That is obviously a drawback for its use as a motor fuel. This disadvantage is not shared by methanol, which can be obtained by further processing (Gondal Hameed and Suwaiyan 2003; Open Source Ecology 2016). Methanol is liquid under atmospheric pressure and ambient temperature. It is also toxic. This last drawback is not shared by dimethyl ether, which can be obtained by further processing of methanol, and also has a higher energy content to weight ratio. Dimethyl ether is an isomer of (has the same chemical formula as) ordinary alcohol but with a different internal structure. At normal temperate zone or tropical temperatures it is a gas, and has broadly the same use characteristics as LPG (Liquid Petrol Gas) (Wikipedia 2016c).

As to sustainable liquid hydrocarbon compounds with longer carbon chains, e.g. petrol/gasoline, diesel fuel, and aviation kerosene, Shell developed a modified form of the Fischer–Tropsch process, which uses methane as its main feedstock (Hoek 2006). This process was evaluated by Goellner et al. (2013) on behalf of the US Environmental Protection Agency, who reported that it was commercially viable. There are two main reasons for part-oxidizing some of the methane to produce carbon monoxide and then applying the original F-T process. The oxidation produces energy, and it pre-empts the formation of molecular carbon (soot). It also facilitates the recycling of other compounds produced by the Fischer–Tropsch process than only carbohydrates. At the time, this process was developed with a view of using natural gas of fossil origin as feedstock. However, the same process can also be applied to methane produced from hydrogen and carbon dioxide.

It is possible to produce methane directly from carbon dioxide and water (Hoeben et al. 2015). Scott (2015) evaluated a similar direct route from CO_2 to methane and reported research on further processing into a range of carbon-containing chemicals.

Either form of producing methane costs energy because recovery of the energy involved in initially heating the gas mixture and transforming water into steam, as well as the reduced caloric value of the methane in comparison with hydrogen is not straightforward: The most obvious process of separating the methane from steam, condensation of the steam into water via heat exchange with cooling water, gives rise to dissipation of this energy into the cooling water.

Whilst methane is suitable for direct use in gas supply, its transport and storage over longer distances are more problematic, even whilst this drawback does not apply quite to the extent as in the case of hydrogen. Methane is a gas at atmospheric pressure and ambient temperature and its storage or transport as a liquid requires facilities keeping it at very low temperatures and/or high pressures. That is obviously a drawback for its use as a motor fuel. This disadvantage is not shared by methanol, which can be obtained by further processing. Methanol is liquid under atmospheric pressure and ambient temperature.

The use of methanol and its further processing into gasoline(petrol)-like substances are also summarized by Wood et al. (2012) as well as the New Zealand Institute of Chemistry (undated). Engines able to run on methanol for maritime shipping are already being built. These engines can run on a range of fuels. The reason for ensure that they can run on methanol appears to be the expectation that tighter regulations on conventional pollution by maritime transport are in the pipeline (Marinelog 2013). So far the most common source of methane to produce methanol is (fossil) natural gas, predominantly consisting of methane (Methanol Institute 2011a). However, these engines could obviously also run on synthetic methanol made from CO_2 and hydrogen, or on methanol made from biogenic methane. Methanol has a lower caloric value than petrol-like fuel. Nevertheless, we may reasonably assume that the construction of ordinary motor car and aircraft engines running on methanol is feasible. After methanol, one step further up on the processing ladder on the chemical route to making automotive fuels such as diesel fuel is dimethyl ether (DME). It is a gas at atmospheric pressure, but unlike hydrogen and methane it does not require extreme pressure to become liquid. It has clear advantages over methanol. Fossil automotive fuels such as petrol or diesel fuel typically have energy values between 40 to 45 megajoules per kg, methanol only 21, and DME 29 (Oak Ridge National Laboratory 2011). Methanol is mildly corrosive to some metals (Methanol Institute 2011b), whilst dimethyl ether is not (New Jersey Department of Health and Senior Services 2002).

Unless the manufacture of such further processed liquid fuels were found to be more cost-effective, the balance of my judgment is that methanol and dimethyl ether will do fine. Ships equipped with engines capable to be run on methanol are now being built (Marinelog 2013). 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”.

Nevertheless, Audi has been running a pilot plant which makes diesel fuel from CO_2 and renewable energy.

> This synthetic diesel, made using CO_2, is a huge success for our sustainability research. If we can make widespread use of CO_2 as raw material, we will make a crucial contribution to climate protection and the efficient use of resources, and put the fundamentals of a “green economy” in place. (Oliver Strohbach, in an Audi press release 2016, referring to a statement of the Federal Minister of Education and Research, Professor Wanka.)

It is understandably that Audi, being a car manufacturer, focuses on automotive fuel, not aviation fuel. However, there is sufficient chemical similarity between diesel fuel and aviation kerosene to make one expect that the same approach would have similar results for aviation kerosene.

Capture of CO_2 from the atmosphere

It is at this point useful to discuss the issue of capturing CO_2 from flue gases and then permanently storing the captured gas, for example, by pumping it under an oil deposit, which is usually itself capped by a salt layer or some similar barrier. This approach is known as “Carbon Capture and Storage (CCS)” and has been advocated by among others Jaccard (2005) as a sustainable way of continuing to use fossil fuels. It has some serious drawbacks. Any capture is partial. In addition, the cost of this approach is enhanced non-trivially by the fact that fossil fuels generally also contain sulphur. Accordingly, 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.

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 Estevan, Saskatchewan, Canada (MIT 2015). The practicality of pumping the CO_2 straight down at Esteven is greatly facilitated by the fact that this place is at the centre of an oilfield. In fact enhanced oil recovery was one of its main purposes, but even so an April 2016 Parliamentary Budget Office report found that CCS at Boundary Dam doubles the price of electricity (Wikipedia 2016e). This cost of CCS is high as it is does not generalize to power stations not situated at such a suitable locations. This form of carbon capture is, I submit, not cost-effective in comparison with desisting from the burning of fossil fuels. However, once there is no significant amount of fossil fuel burning left, the manufacture of synthetic hydrocarbon fuels will have to use CO_2 from the atmosphere.

The pilot plant reported by Scott (2015) uses captured CO_2 from a nearby ammonia producing plant. In this context, the acronym CCU (“Carbon Capture and Use”) is used. However, this is not really good enough. At around 400 ppm, the existing CO_2 content of the atmosphere is already unsustainable. The excess of the energy over the incoming sunlight over that of the earth’s outgoing infrared heat radiation is so far being absorbed mainly by the oceans which have an enormous thermal mass. However, we cannot go on adding even more. On the contrary, I agree with Hansen et al. (2008) that we need to *reduce* the CO_2 content of the atmosphere. There are processes to do exactly that:

> The process uses a large wall of fans, known as a contactor, to push air through a liquid that reacts with the CO2. That carbon dioxide-rich solution is then

> put through several processing steps to create a purified stream of CO2 gas and the liquid that is returned to the contactor. (Martin 2015)

The word “contactor” here means “air contactor”, i.e. the unit in which the CO_2 is actually captured by a chemical process, whilst the capturing chemical (which does not have to be a liquid) is recycled after having released the CO_2.

In this context, I note the following conclusion of (quote from) IEAGHG (2015: 2), concerning DAC (Direct Air Capture) referring to the abstract of House et al. (2011):

- DAC is significantly more expensive than other low-carbon mitigation options and thus will not be competitive with CO_2 capture at power plants and other large point sources.
- Costs of DAC are likely to be of the order of \$1000/t of CO_2 avoided.

CO_2 capture, whether in CCU from flue gases or for CCS to reduce the CO_2 content of the atmosphere, or indeed, in CCU to make renewable fuel, is inevitably partial. In addition, as more and more use of fossil fuel is phased out to be replaced by renewable forms of energy there is bound to be an end to CCU capture from flue gases arising from the combustion of fossil fuels. I would also guess that further development of the synthetic liquid fuel technology, with some readily transportable liquid fuel being pumped back into oilfields might be a practical technology for reducing the CO_2 content of the atmosphere. Clearly this requires some kind of multi-national arrangement to finance such negative emissions, an issue which goes beyond the remit of his article.

As to the cost of air capture, reference to the full text rather than the abstract of House et al. (2011) to which IEAGH above refers shows that a major part of the energy cost of the process envisaged for capturing CO_2 from the atmosphere arises from driving air over or through the CO_2 absorbing chemical, using fans.

Fans are, however, not the only possible method to create the necessary airflow. Czisch (2011: 141 ff), referring to Carlson (1975) mentions cooling air in downdraft towers by spraying water in dry warm air at the top as a source of power to drive a turbine. Note that the cooling effect of evaporating water is so strong that even though water vapour is added to the volume, the mixture of water vapour and cooled air nevertheless becomes heavier for the same volume due to the cooling of the air. This is the reverse process of a rising thundercloud, which is lighter than the surrounding air, even though water vapour has lost most of its volume by condensing into fine droplets.

As a method of generating renewable forms of energy, downdraft towers may not be cost-effective in comparison with other types of equipment such as solar panels. However, as a method of creating an airflow it may well be more cost-effective than installing fans and running them on electricity from the grid. Building such towers with or without a turbine but in any case a CO_2 capturing sorbent at the bottom may possibly be more cost-effective than using electriciy to power fans.

In a hot desert area near the sea such a structure would integrate quite well with Concentrating Solar Power, in combination with making synthetic fuels: The CSP power station would use sea water as coolant, and the waste heat can be used to desalinate sea water (DESERTEC UK 2013). The fresh water could then be used to create the airflow in the downdraft tower, as well as for other uses such as irrigation. A further advantage of the co-integration of downdraft towers with CSP would be the potential to make synthetic hydrocarbons: Hydrogen would be generated when the power output of the CSP power station exceeded the demand for electricity, and the hydrogen would then be processed with the captured CO_2 into methane and/or further into liquid hydrocarbon compounds. It should be possible to design a co-integrate facility which combines CSP with the Sabatier process to make methane. A significant part of the waste heat of both the condenser unit of the CSP station and the Sabatier process could then be recovered and used to convert sea water into fresh water. The result would be a capability to export electricity as well as liquid fuels, whilst generating an agricultural potential which was not there before.

Biofuels

Here Duić (p. 2095) quite rightly points out that this is an inefficient use of land. The fact that his figure for the thermal efficiency of photovoltaic panels of 15 % and upwards requires a rather liberal interpretation of “upwards” only strengthens this argument. What he seems, however, to be unaware of is the fact that biofuels are in fact via the demand for new cultivation land and its effect on deforestation, extremely counterproductive in terms of emissions reduction (Hooijer et al. 2006).

The socio-economic dimension of the transition

In his introduction, Duić correctly mentions the two sides of this issue: The employment side and the fact that past investments in the fossil fuel-related technology have been financed on credit that needs to be repaid.

Of these two problems, the first one is to a degree ameliorated because there is a fair degree of overlap in the expertise required to build wind farms and oil platforms. Statoil, the Norwegian state owned oil company took, presumably with the encouragement of its sole owner, the Norwegian government, a decision to diversify into renewables (Statoil 2003). It has now contracted to build now build a 30 MegaWatt pilot project *floating* wind park consisting of 5 turbines of 6 MW which is to be built off the East Coast of Scotland (Renewable Energy World 2016). This project is at the front end of the offshore wind turbine construction. To stabilize the turbines in the ocean swell, they will each have an underwater steel and concrete counterweight (Siemens 2016b).

In addition, the unemployment problem related to the phasing out of fossil fuels is somewhat mouse-sized in comparison with the elephant in the room, which is robotics and computerization.

David Zeiler, writing in the US financial magazine *Money Morning* (2013) refers to a report by Kevin Kelly in *Wired* (2012) which forecasts that 70 % of US current jobs will have gone by the end of the century.

The traditional economist's response to this issue is that further economic growth will create new employment opportunities. That approach is no longer sustainable, because climate stability is only one of a whole range of planetary boundaries (Rockström et al. 2009) which are threatened by unbridled economic growth. Sooner or later, humanity needs a social organization in which the social requirement of earning one's living by paid work does not make us addicted to economic growth. However, just now, the environmental Kuznets (Stern 2003) concept is coming to humanity's help once more, by providing a technological remedy. If this opportunity is grasped at an adequate level, the Keynesian multiplier effect of investment in renewable forms of energy creates more additional jobs offering a chance to maintain social normality and indeed, to build, for a whilst, a fairer world, where unemployment is less of a driver of inequality.

I am more concerned about the any detrimental financial consequences when stranded assets have to be written off. This is an additional cost of past investment in a technology which should have been regarded as obsolete long ago. Such a development could result in serious difficulties in 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 properly, 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 even though 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.

Concluding remarks

I must express some doubt as to whether the body of Duić's article adds up to the conclusion at the end of the article that clean energies could be completely or nearly so be in place by 2050. What brings the issue into even sharper focus is the circumstance that (as Duić correctly comments) this might be too late to save the climate. Without the HVDC technology and/or more speedy development and production of synthetic fuels than Duić envisages, it is difficult to see how adequate winter heating could be provided in the sub-arctic climate zone. There the mid-winter sunshine is only a few hours per day and at a low angle, with outside air temperatures of several tens of degrees centigrade below zero, with essentially windless frosty weather being common. Yet several major cities, such as the capitals of Norway and Sweden, Oslo and Stockholm, as well as Russia's second city, St. Petersburg, are in this area. I also have my doubts whether, quite apart from maritime transport and aviation, the full scale switch of land transport to electricity will become a reality without banning the sale of fossil motor fuel.

On the other hand, once the HVDC technology and the manufacturing of synthetic fuels are implemented with reasonable speed, a much earlier date then 2050 is no technological problem. That does, however, bring in its wake the requirement to face the consequences of past investments in fossil fuel exploration and in equipment using it being seen to be stranded assets.

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