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The implication for climate change and peak fossil fuel of the continuation of the current trend in wind and solar energy production

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ABSTRACT

Climate change, and more recently, the risk of fossil fuel production being unable to keep pace with demand (peak fossil fuel) are both considered as risks to civilisation, or global risks. In an initial empirical analysis, this paper attempts to answer the following questions, which have often been posed but have not, to our knowledge, been answered empirically at global level. At which date, if unaddressed, will the risks become critical? Given that the substitution of fossil fuels by wind and solar energy is often proposed as a solution to these problems, what is its current aggregate growth rate and is there a plausible future growth rate which would substitute it for fossil fuels before the risks become critical? The study finds that the peak fossil fuel risk will start to be critical by 2020. If however the future growth rate of wind and solar energy production follows that already achieved for the world mobile phone system or the Chinese National Expressway Network the peak fossil fuel risk can be prevented completely. For global warming, the same growth rate provides significant mitigation by reducing carbon dioxide emissions from fossil fuels to zero by the early 2030s.

Global warming, which is contributed to substantially by the burning of fossil fuel – coal, oil and natural gas – has for a substantial period been recognised as a risk to civilisation (United Nations, 1992). Further, it is recognised that the risk is intensifying. According to a joint statement of the academies of science of the G8+5 (2009) countries in 2009:

> "Climate change is happening even faster than previously estimated; global CO_2 emissions since 2000 have been higher than even the highest predictions."

If this was not bad enough, in recent years it is being increasingly acknowledged (for example, Nel and Cooper, 2009; Heinberg and Fridley, 2010) that a second significant risk to civilisation arises from fossil fuel – its likely near-term peaking in production – often called "peak fossil fuel". Peak fossil fuel (Bardi, 2009) is a term that summarises the concept that the production of fossil fuel grows, reaches a maximum (peak), and then gradually declines so that it increasingly cannot meet demand (except at much higher prices, which prevent its use in as widespread a way as today).

The solution most frequently proposed for both minimising the climate change risk and preventing the peak fossil fuel risk is to progressively transition from fossil fuel to non-fossil fuel energy (for example, Pacala and Socolow, 2004). Detailed quantitative studies now suggest that it is possible, and also affordable, to make the transition (for Australia, Beyond Zero Emissions (2010); at worldwide scale, Jacobson and Delucchi (2011) and Delucchi and Jacobson (2011)) and primarily relying on wind and solar energy. Delucchi and Jacobson (2011) further find that such energy sources can meet the energy needs of each energy-use sector (electric power, transportation, and heating/cooling).

The latter authors also claim that the transition can be made in the near term – for all new energy requirements by 2030 and to replace all existing energy by 2050 – but make no quantitative assessment of whether or not this timeframe would mean the risk would be addressed in time.

We have not found any analysis, which compares actual trends for both the global warming and peak fossil fuel risks and for the potential non-fossil fuel energy response that will allow a quantitative assessment of the explicit question of (i) when the risks become critical, and (ii) whether the response can be at an adequate scale before then—in other words, be in time.

This paper addresses this question. In doing so, simple empirically-based scenarios are presented: first on the likely timing of the onset of each of the two risks at civilisation-disrupting level, then on the potential timing of the development of future wind and solar power production. The intersection of these trends is then presented and assessed to give a quantitative estimate of the possible timing of the transition and its adequacy to meet the risk.

This analysis is carried out from a prudent risk-management perspective: that is, the scenarios addressed are plausible worst-case scenarios for each risk and plausible best-case scenarios for

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achieving full, or the maximum possible, prevention of the risks. The plausible worst-case scenario for peak fossil fuel is the earliest peak for which there are a substantial number of analyses published in the peer-reviewed literature. The plausible worst-case scenario for climate change consists of the worst plausible results for the indicator outcomes – flood and drought are taken as the indicator outcomes (see later) – again, for which there are trend analyses published in the peer-reviewed literature. The best-case scenario for achieving full, or the maximum possible, prevention of the risks is defined here as the strategy, which can achieve full or the maximum mitigation at the earliest juncture and affordably. In regard to this approach to mitigation, in the words of the Australian government's climate advisor (Garnaut, 2011):

> "The principles of prudent risk management dictate that the case for action is strengthened, rather than diminished, by the fact that outcomes could turn out far worse… than we expect. With strong mitigation, we at least rule out, or reduce to low probabilities, the potential for catastrophe."

Turning firstly to peak fossil fuel, Table 1 provides summary statistics from studies of peak fossil fuel in terms of the average and standard deviation of peak year by fossil fuel type. The majority of the sources are from the comprehensive review of estimates for future global commercial fossil fuel production provided in Mohr (2010). For the present table these results are augmented by the further results of Mohr (2010) itself, and of Nel and Cooper (2009). The combined pool of such studies numbered 36, and contained a total of 68 estimates of fossil fuel peaks. Concerning aggregate statistics on the sources of the estimates, 57 per cent were from peer-reviewed journals, 11 per cent from books or government reports, 14 per cent from conference or workshop proceedings and 18 per cent from studies published on the internet. Table 1 shows that all fuel types except coal are found to peak before 2030 and the average of the estimates for the peak of fossil fuel production is the year 2028. This is the case even though the peak for coal is estimated as further into the future, at 2049.

It can be seen from Table 1 that even if, by adding one standard deviation, one focuses on the estimates suggesting that there are more resources, peak fossil fuel is still seen to occur no later than the mid 2030s.

With this background, the plausible worst-case scenario value chosen for use in this study for the timing of the peak fossil fuel risk is the mean estimate, 2028. The mid-range "Reference Case" estimate of the study of Nel and Cooper (2009), at 2025, is closely similar. As this estimate is recent, provides detailed trend information and is from a peer-reviewed journal, it is used as the reference case and dataset for peak fossil fuel for the rest of this paper.

Fig. 1, covering the 1970–2050 period, shows the full Nel and Cooper (2009) fossil fuel production trend in graphical form. A selected cross-section of further production trends drawn from the studies summarised in Table 1 is also displayed. These include two earlier-peaking estimates, with peak dates at around 2020 (de Sousa, 2008; Laherrere, 2006).

Other major groups with an interest in fossil fuels are governments and producers. The government-agency current estimates (European Commission, 2006; International Energy Agency (IEA), 2010) do not show a peak for peak fossil fuels as a whole. However, with regard to oil, the International Energy Agency's latest annual World Energy Outlook (IEA, 2010, p. 125) both acknowledges peak oil and specifies a peak production year for crude oil output, – 2006 – which means that the IEA considers that peak oil has already occurred. This is in contrast to previous reports in which the IEA had predicted that crude oil production would continue to rise for at least another two decades.

Finally, it is noteworthy that two major oil firms, in their current official publications, have illustrated total fossil fuel production either clearly peaking by 2035 (Shell, 2008), or, in data provided only to 2030, its rate of growth slowing (BP, 2010).

As mentioned, peak fossil fuel becomes a problem if, when added to other conventional energy sources such as nuclear and hydro, it cannot meet demand for energy in the future.

Table 1
Literature fossil fuel peak year estimates.

Fossil fuel type	Number of estimates	Peak year estimates	
		Average year	Standard deviation (years)
Conventional oil	28	2016	12.8
Conventional plus unconventional oil	17	2022	18
Gas	9	2022	9.4
Coal	7	2049	25.9
All fossil fuels	7	2028	8.5

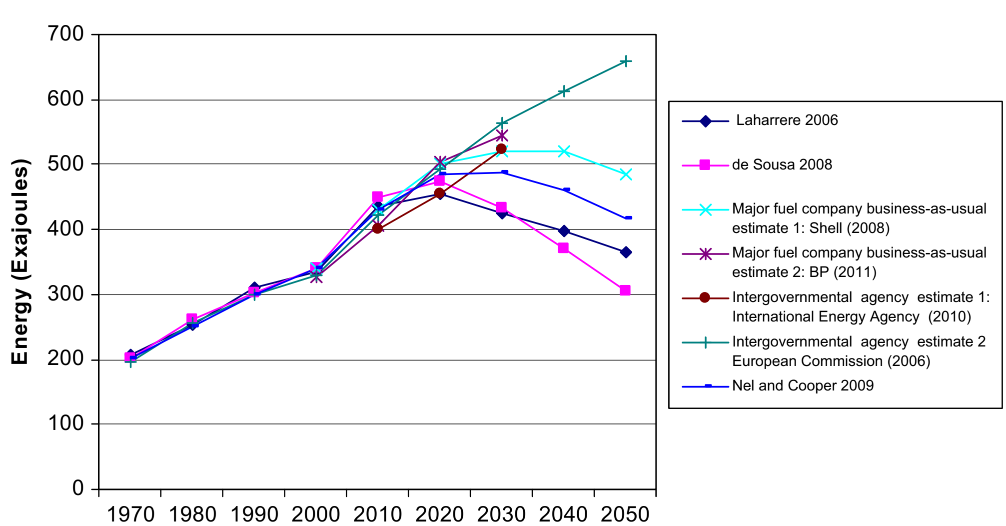

Fig. 1. A range of estimates of global fossil fuel production to 2050.

Nel and Cooper (2009) comment on the gravity of the implications of this outcome:

> "It is … considered as unlikely for the current Western economic paradigm to be sustainable…"

Even for the peaking of oil alone, a report commissioned for the U.S. Department of Energy (National Energy Technology Laboratory, quoted in Hirsch et al. (2005)) states:

> "The world has never faced a problem like this. Without massive mitigation more than a decade before the fact, the problem will be pervasive and will not be temporary. Previous energy transitions (wood to coal and coal to oil) were gradual and evolutionary; oil peaking will be abrupt and revolutionary…"
>
> "As peaking is approached, liquid fuel prices and price volatility will increase dramatically, and, without timely mitigation, the economic, social, and political costs will be unprecedented."

Fig. 2 depicts estimated world primary energy demand compared with the sum of, and current projected growth in, production of non-fossil fuels (including conventionally-projected solar and wind power) and fossil fuels. Two official estimates are given of world primary energy demand (European Commission, 2006; International Energy Agency, 2011). Despite the difference in the publication dates of the estimates, they agree closely. The year at which the trends for energy demand deviate from that of supply indicates the beginning, if we do nothing to rectify the trends, of the deleterious economic and social impacts from peak fossil fuel of the type outlined above. The year is around 2020, at the start of the plateau leading to the predicted peak of fossil fuel production later in the 2020s.

Turning now to global warming, Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) commits its signatory nations to stabilizing greenhouse gas concentrations in the atmosphere at a level that "…would prevent dangerous anthropogenic interference with the climate system." The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) (2001) identified five "reasons for concern" that would indicate (Smith et al., 2001) such dangerous anthropogenic interference. One of these is "Risk of Extreme Weather Events" and we use this indicator in this paper—specifically the extreme weather events of drought and flood. This is done not least because of their link to food supply (Battisti and Naylor, 2009). Fig. 3 presents results from studies projecting drought and flood events to 2100 both under IPCC (non-peak fossil fuel) scenarios (Sheffield and Wood, 2008; Hirabayashi and Kanae, 2009), and for these results amended in light of the Nel and Cooper (2009) peak fossil fuel scenario. The models from the IPCC use a mid-range scenario for temperature rise in the 21st century.

According to climate change theory (for example, Nel and Cooper, 2009) the smaller amount of fossil fuel burned because of peak fossil fuel is expected to lead to lower carbon dioxide emissions. In turn, this results in a smaller temperature rise, and therefore reduced incidences of flood and drought over that otherwise expected. The estimation of the changed flood and drought trends expected from peak fossil fuel was carried out as follows. A mid-range temperature trajectory for the 21st century had been derived by Nel and Cooper (2009) from the Reference Case trend in their paper used in this study. Flood and drought trends for the 21st century were obtained from the studies of Hirabayashi and Kanae (2009) and Sheffield and Wood (2008), respectively. Both flood and drought studies showed a clearly linear relationship between level of global temperature and level of flood and drought: (flood $r^2=0.967$; drought $r^2=0.974$). Given this, the new expected flood and drought trajectories were calculated by linear regression substituting the temperature trend used by the flood and drought studies (the IPCC mid-range A1B estimate) with the Nel and Cooper (2009) temperature trend. For the period 1970–2100 Fig. 3 plots the peak fossil-fuel flood and drought trends so obtained and also provides comparison with those from the IPCC A1B temperature scenarios.

Even under the peak fossil fuel scenario with its milder effect on global warming, the figure shows that by 2100, the number of people affected by flood is projected to treble, to half a billion people, and the land surface affected by drought is likely to increase by one quarter to 15 per cent of total world land area.

As mentioned, the solution most frequently proposed for both minimising the climate change risk and preventing the peak fossil fuel risk is to progressively transition from fossil fuel to renewable energy – primarily wind and solar – before the dates described above. In this connection, markets via the price mechanism will increasingly assist: as the IEA (2010) states: "…renewables are expected to become increasingly competitive as fossil-fuel prices rise and renewable technologies mature…"

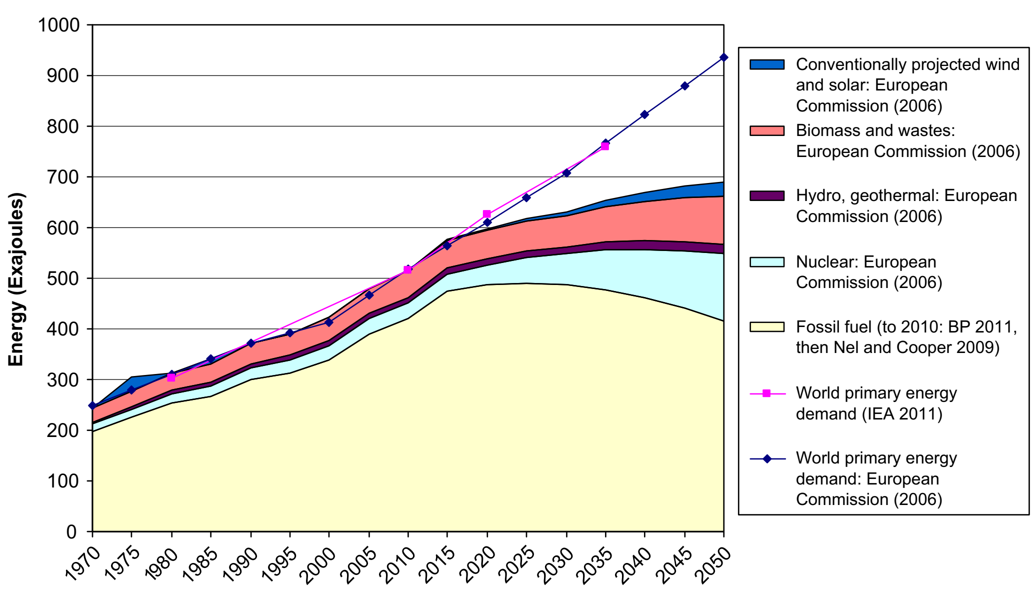

Fig. 2. Energy demand and supply under peak fossil fuel.

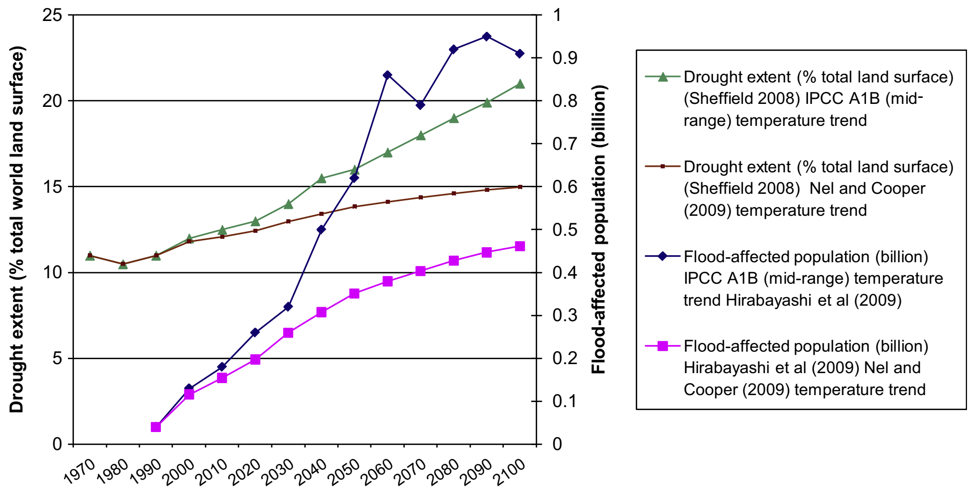

Fig. 3. Projected trends in severe weather events.

That said, a number of authors have called for crash programs to accelerate the transition (Hirsch et al., 2005; Friedman, 2008; Gore, 2009; Beyond Zero Emissions, 2010; Delucchi and Jacobson, 2011). A key aspect of any such proposed programme is its time course and its plausibility. We have been able to find only one study (Kramer and Haigh, 2009), which quantitatively depicts energy trends to the future to assess the question of adequate timeliness and which also quantitatively assesses proposed precedents to assess plausibility. From their study Kramer and Haigh state that:

> There have been high-profile proposals to 'repower' the world in a decade, loosely based on the way innovative consumer goods such as mobile phones or iPods conquer their markets. Unlike with consumer goods, we believe that there are robust empirical 'laws' that limit the build rate of new and existing energy technologies and thereby the potential to deliver much of the hoped-for transformation by 2050.

This is because

> When (energy) technologies are new, they go through a few decades of exponential growth… until the energy source becomes 'material'—typically around 1% of world energy. After reaching materiality, growth curves have historically levelled off.

We submit, however, that the paper was operating under different assumptions to those of the present paper. The major planks of Kramer and Haigh's case all presume that (i) the energy sources are present in a market with available fossil fuels, and that (ii) neither fossil fuel depletion nor global warming from fossil fuel exist as policy or consumer drivers away from fossil fuel to a new zero-carbon energy mix.

That said, Kramer and Haigh then go on to state that the trend patterns seen in new energy market penetration can be "…outperform(ed)… by designing energy policies directed at decarbonising the energy industry."

Having provided this hopeful prospect, they then report on the Shell company's 2008 energy scenarios, one of which (Blueprints) has "optimistic projections" for new energy deployment. But even here, renewable energy met only "one-quarter of the total demand for energy" at 2050.

Most fundamentally, despite their article commencing with reference to non-energy precedents – "innovative consumer goods" – which we have noted have not been quantitatively assessed Kramer and Haigh (2009) then went on to assess only energy precedents.

The present paper therefore asks, quantitatively, the following: Are there other relevant examples of similarly scaled technological infrastructure, not limited to energy examples, which have in the past already achieved or nearly achieved, the needed 100% market penetration? If so, are there patterns in their trajectories and rates of growth, which can throw light on the speeds possible to achieve near 100% market penetration for wind and solar energy?

If these patterns exist, they could form the sought plausible best-case mitigation scenario against the risks from climate change and peak fossil fuel—that is, a quantitative case depicting the fastest plausible deployment of wind and solar energy for any thoroughgoing attempt to achieve the goal of meeting all world primary energy demand at the earliest juncture.

The growth of technological infrastructure has been studied under such names as technology diffusion, technological substitution and market penetration. There are two main categories of such technological product (Van der Vooren and Alkemade, 2010): simple consumer technologies; and large infrastructure dependent technologies—physical networks such as transportation, energy supply and communication systems. It is this latter group, which is most comparable to wind and solar energy production systems.

With regard to such infrastructure Van der Vooren and Alkemade (2010) state: "The work of Grubler on the rise and fall of infrastructures shows clear patterns in technological substitution and succession of complex systems." According to Grubler (1990): "This type of growth is that of growth in interaction with a (limiting) environment". The curve for such growth is S-shaped, and is often modelled using the logistic function.

Fig. 4 shows growth trajectories for major representative examples of transportation, energy supply and communication systems. Examples are at least at the level of major nations or are at global level, and the non-wind and solar examples have achieved full or near full market penetration.

Specifically, reading left to right across Figure 4 in general order of historical occurrence, the examples are: US domestic electrification (Moore and Simon, 1999); radio in the US (Carter et al., 2011); television in the US (Carter et al., 2011); US Interstate Highway System (Cox, 2011); China National Trunk Highway System (actual: National Bureau of Statistics of China (2011); projected: Dingding (2008)); world mobile cellular telephone subscriptions (Mobil and Veckans Affärer, 2006;

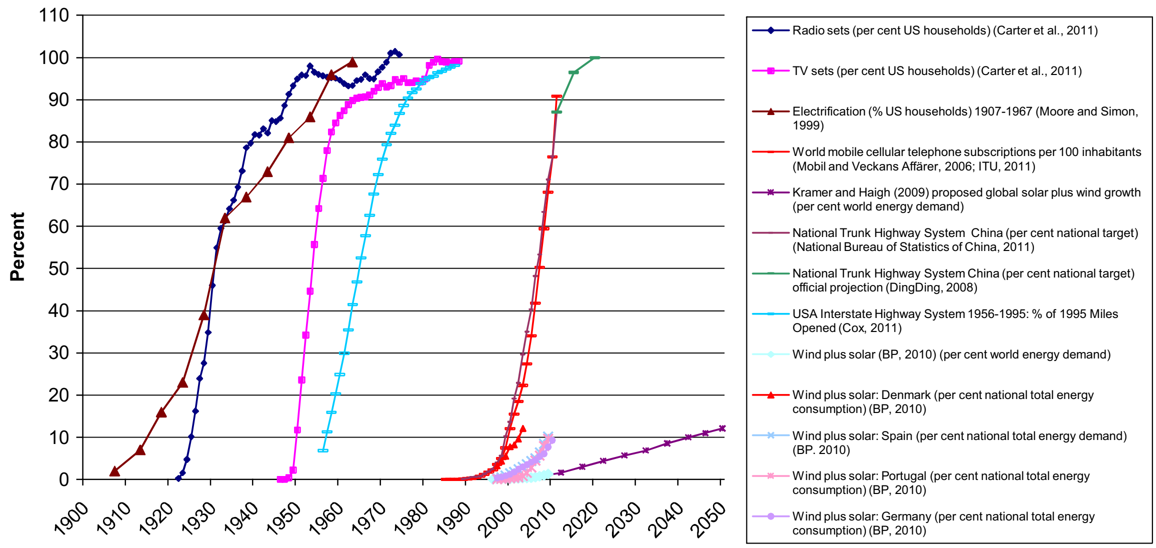

Fig. 4. Growth of major transport, energy supply or communication systems.

Table 2
Large scale infrastructure: growth time and cost.

	Year of inception	Years taken to grow from 10% of market penetration or target to 90%	Annual cost as per cent GNP/GWP	Source for cost
Electrification (US)	1882	42		
Radio (US)	1922	23		
Television (US)	1946	14		
Interstate Highway System (US)	1956	19	2	Jones (2008)
Global mobile phone system	1985	11	3.8	International Telecommunications Union (2011)
National Expressway Network China	1989	13	1.7	World Bank (2007)
Global wind and solar energy production	1980	8	3	Beyond Zero Emissions (2010)

International Telecommunications Union, 2011); wind and solar energy production for Denmark, Germany, Spain, Portugal and world (BP, 2010); proposed future world wind and solar energy market penetration trend (Kramer and Haigh, 2009).

The visual examination of the growth curves in Fig. 4 shows that all the curves exhibit much more rapid growth past the 1% market penetration level than suggested likely for new energy technologies by Kramer and Haigh (2009). This is true not only for all the non-energy examples, but also for the energy examples—the wind and solar deployments of the four countries, which have grown wind and solar energy fastest (BP, 2010).

Most of the growth curves are clearly of the S-shaped form. It is therefore noted that the likely future trajectory of the currently exponential global wind plus solar production trend will not remain exponential but be of the S-shaped, logistic form.

Are, then, some of the curves shown in Fig. 4 more plausible precedents than others for future wind and solar energy production? This is explored via quantifying the growth rates shown in the figure. A simple way of measuring the rate of growth of S-shaped curves (Grubler, 1990) is in terms of the time interval taken for growth to occur from 10% to 90% of market penetration. This data for examples in Fig. 4 is provided in Table 2.

The examples shown in Table 2 enable the speculation that rates of implementation are fastest when there is a strong imperative to achieve a goal, either by citizens for new consumer technology when it is affordable – radio, TV, and mobile phone – or by governments for national-scale infrastructure considered strategic economically and/or for defence. The table also shows that growth rates in more recent times are quicker than those of earlier periods.

Fig. 5 quantifies a further factor shown in Fig. 4: that different technologies have shown different growth rates at different stages of the growth curve.

Fig. 5 shows that despite its acknowledged history so far of rapid and exponential growth, growth in global wind and solar power has in fact been slower than other major technologies in growing from 1% to 10% of market penetration. By contrast, continuation of its current exponential growth path would enable it to reach a 90% market penetration at a similar rate displayed by such examples of these infrastructures as US television, the global mobile phone system and the Chinese National Expressway Network.

With this background, what is a plausible best-case scenario for earliest potential prevention or mitigation of the climate change and peak fossil fuel risks? This means best possible performance rather than average performance—in other words, how fast demand can be met or supply provided when an imperative exists. On this basis, the plausible growth scenario chosen for use in the remainder of this paper is the average of the growth performance of the global mobile phone rollout and the development of the Chinese National Expressway Network. It is considered that these instances are further comparable in terms of scale of cost. Table 2 shows that the annual cost of the two rollouts is 3.8% of gross world product (GWP) and 0.53% of gross national product. This compares with that estimated for the full-scale rollout of wind and solar energy globally—some 3% of GWP per year (Beyond Zero Emissions, 2010; DeCanio and Fremstad, 2011).

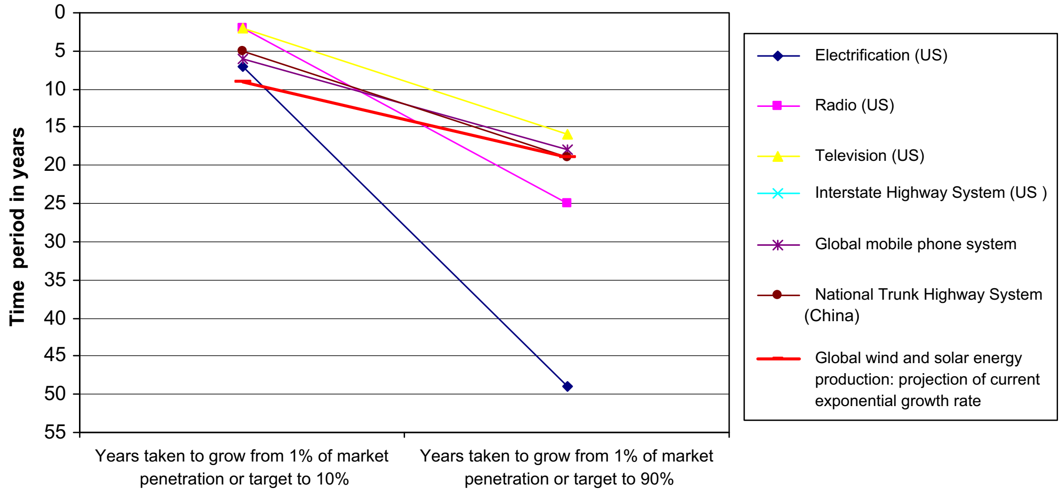

Fig. 5. Comparative growth rates of large technology systems at two stages of the growth trajectory.

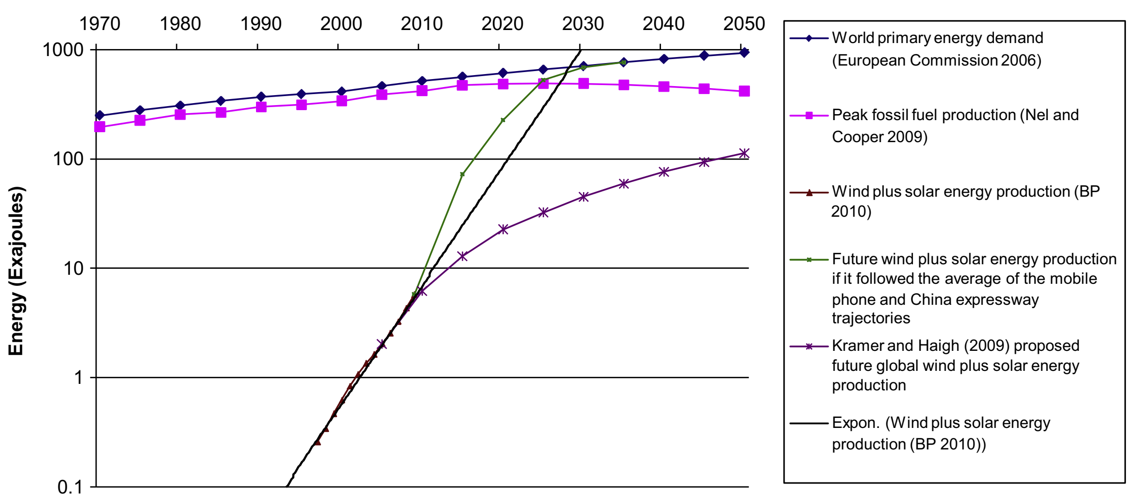

Fig. 6. Potential growth trajectories for world primary energy demand and selected energy production categories.

How then, does the proposed plausible potential mitigation trajectory (termed for convenience here the mobile phone/China Expressway trajectory) interact with the risk trajectories? Fig. 6 provides information not in market penetration terms but in terms of the underlying market factors – world primary energy demand, and the proposed potential supply – which would arise if the mitigation trajectory were followed. The continuation of the exponential growth rate for wind and solar energy to date is also plotted in the figure.

In Fig. 6, the logarithmic scale used shows that, to date, past wind and solar growth has been clearly exponential (R-square = 0.996). If that growth rate were to continue, the date at which the wind plus solar curve meets the primary energy demand curve is the date that all marketed world energy demand could be met by wind and solar power generation. The figure shows that the date is around 2028. Because of the nature of the S-shaped growth curve, it can be seen that the intersection with the demand curve is only slightly later, around 2030. The Kramer and Haigh (2009) projection is plotted for comparison.

The implications of the trends in Fig. 6 are quantified in Fig. 7.

In Fig. 7 the dark blue curve indicated by diamonds is world primary energy demand. The purple curve indicated by squares is total conventionally projected energy production. The yellow curve indicated by triangles is the provision of wind and solar energy under the mobile phone/China Expressway growth rate scenario. The light blue curve indicated by squares is the amount per year of non-wind and non-solar energy required to meet demand if newly available wind and solar energy always displaces non-wind and non-solar energy. It is seen that the light blue curve with squares curve never rises above the dark blue demand curve. This shows that the sum of conventional energy and newly available wind and solar energy under the mobile phone/China Expressway scenario is always sufficient to avert supply shortages—that is, the peak fossil fuel risk is fully averted.

The figure also shows that under the mobile phone/China Expressway scenario, by 2035, wind and solar energy could meet all world primary energy demand.

Turning to global warming, Fig. 8 shows the effect specifically on fossil fuel consumption of the continuation of the wind and solar energy growth trajectory under the mobile phone/China Expressway scenario.

The figure shows that the continuation of the wind and solar growth trajectory at the growth rate for the mobile phone/China Expressway systems has the capacity to cause the complete cessation of fossil fuel use – and therefore the reduction of new carbon dioxide emissions from fossil fuel entering the atmosphere to zero – as soon as 2024.

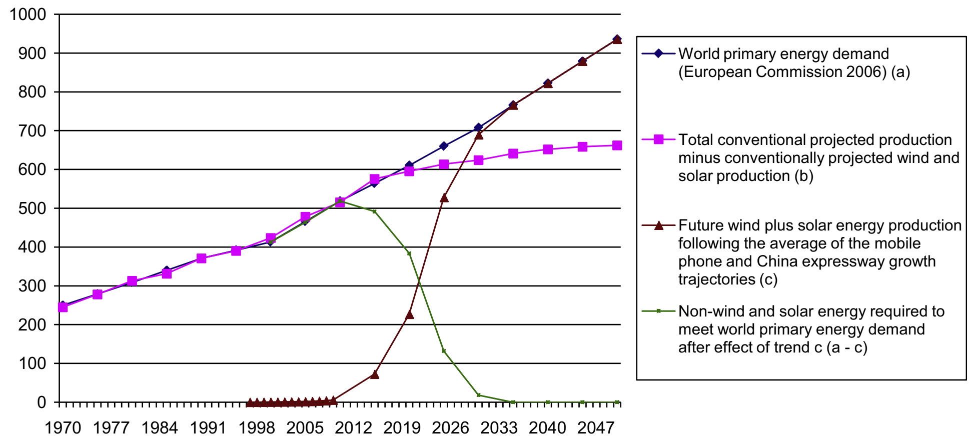

Fig. 7. Effect by year of wind and solar energy production growing at the mobile phone/China Expressways growth rate on the requirement for nonwind and solar energy production. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

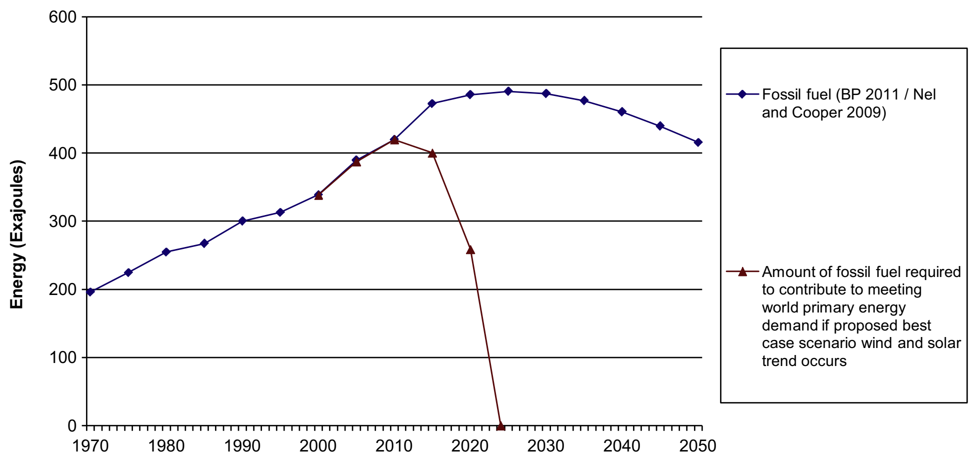

Fig. 8. Global warming risk: effect of wind and solar growth trajectories on fossil fuel consumption, overall world energy demand being met.

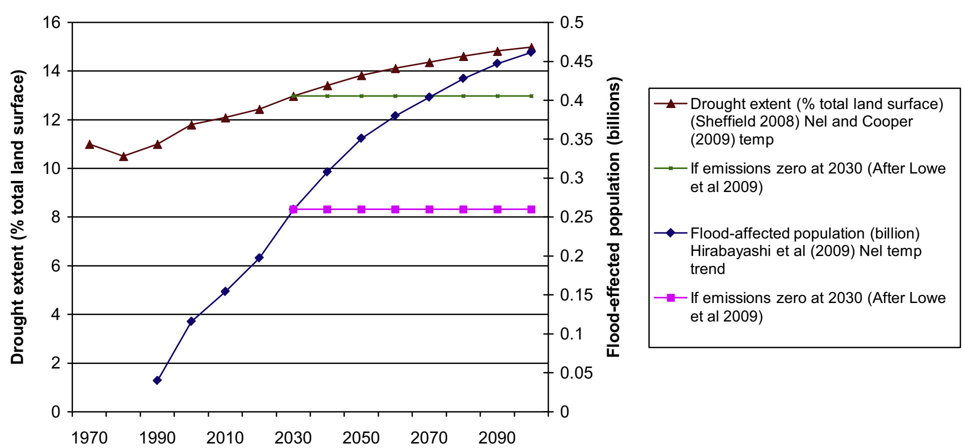

Fig. 9. Projected trend in flood and drought with and without continuation of current wind and solar energy growth rates.

Looking at the outcome for the climate of reaching this important emission-reduction milestone, it is well understood that, based on earth system thermodynamics (Lowe et al., 2009; Monastersky, 2009), this cessation of emissions will not result in a cessation of global warming, but rather will place a cap on further warming, with climate recovery occurring only over, as Lowe et al. (2009) state, "…very long … timescales". Study of the results on which this observation is based shows that these timescales mean the outcome is little different from stasis in temperature for the first century after any cessation of emissions. This is depicted after data from Lowe et al. (2009) in Fig. 9.

These results are still worthwhile, however. They represent prevention of two-thirds of the progression up to 2100 along the increasing flood and drought trajectories that even a peak fossil fuel-constrained warming has in prospect for us. This prevention is potentially of great value when linked to the observation of Battisti and Naylor (2009) about events which have already occurred:

> "The food crisis of 2006–2008 demonstrates the fragile nature of feeding the world's human population. Rapid growth in demand for food, animal feed, and biofuels, *coupled with disruptions in agricultural supplies caused by poor weather* (author emphasis added)… have created chaos in international markets."

Given then the important apparent benefits to civilisation of future wind and solar energy production growing at the rate of the proposed precedents – the global mobile phone system and the Chinese National Expressway Network – it is worth reiterating points concerning its feasibility. Both the proposed precedents *have already been built* – to the stage of achieving around 90 per cent of market penetration or of national target. That equivalent degree of rollout for global wind and solar energy by itself would fully prevent the peak fossil fuel problem and greatly mitigate the global warming risk and the precedents are on target to reach the 100% figure in the near term. Further, the capital required for the precedents has been very much of similar magnitude to that estimated to be required for the wind and solar energy systems. This capital has been formed, and difficulties, especially those of implementation, overcome. This has all been done, in the scheme of things, without great controversy.

The foregoing analysis should therefore assist in giving decision makers confidence that supporting the future growth of wind and solar energy production along the lines of the precedents already achieved is worthwhile. As well, the sets of future trajectories used in this paper both for the climate and peak fossil fuel risks and for the wind and solar energy response may provide a useful means of monitoring progress along a path that can bring us safely through.

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