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Principles of sustainability and physics as a basis for the low-carbon energy transition

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Abstract: Human society needs to achieve a low-carbon energy mix this century. To achieve this, we need: (a) an appreciation of the value of Earth's atmosphere; and (b) a sustainable approach for low-carbon energy. For sustainable developments, three pillars need to work together: the environment, social equity and economics. To address the societal aspects of the low-carbon energy transition, we need to appreciate that our future depends on protecting the Earth's atmosphere. By reviewing the discovery of the greenhouse gas effect over the last 200 years, we establish the essential motivation for changing human behaviour with regard to energy use. From this basis, we consider the challenge of how to achieve this energy transition or, more specifically, how to overcome the dissonances related to societal acceptance, economic hurdles and lack of progress with deployment of low-carbon energy options. The last decade has seen a significant growth in the renewable energy and natural gas sectors: however, CCS has made limited progress. This has to change if the human population is to significantly reduce greenhouse gas emissions. In order to accelerate reductions in global CO_2 emissions, all low-carbon energy options must be deployed at an increasing rate in the coming decades.

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Reduction in global greenhouse gas emissions is now widely agreed upon as a key issue for modern human civilization. With around two-thirds of current greenhouse gas emissions coming from the energy sector and with 82% of world energy supply (in 2014) coming from fossil fuels (IEA 2016*a*), the transition to low-carbon energy systems is consequently an urgent priority. Despite widespread agreement on the need to control greenhouse gas emissions, there are many diverging opinions on how this should be achieved (Bale *et al.* 2015) along with political and social resistance to implementing the changes involved (Geels 2014). Debate about the causes of recent climate change and some dissenting voices questioning whether such an energy transition is actually needed (Hulme 2009; Stoknes 2015) creates a degree of confusion about the reasons for, and urgency of, this transition to a low-carbon energy system.

This energy transition is intimately connected with the concept of sustainable development, which was defined by the United Nations Brundtland Commission (in 1987) as development which meets the needs of the present without compromising the ability of future generations to meet their own needs. This principle clearly applies to modern human society (Grubb 2014) where industrial development since about 1750 has been based on a rapid growth in the use of fossil fuels and in the CO_2 emissions to atmosphere resulting from their combustion (Andres *et al.* 1999). In studies of sustainability, is it widely argued that the three pillars of sustainability need to work together, namely: (a) the environment; (b) social equity; and (c) economics. The challenge for the transition to low-carbon energy systems, desirable from an environmental point of view, is therefore to find transition mechanisms that are both economically viable and socially acceptable. Achieving this transition in a sustainable manner is a highly complex problem (Grubb 2014) but, nevertheless, an essential challenge to address. Sachs (2015) has argued that sustainable development is now so fundamental to our modern society that sustainability principles should be the norm for solving a broad set of global problems, not least the energy transition.

The aim of this paper is to review the scientific basis for the low-carbon energy transition, recognizing many other important and more comprehensive reviews that have focused on the climate change aspects (Stocker 2014), the socio-economic aspects (Stern 2007; Grubb 2014) and the psychological aspects (Stoknes 2015). After briefly reviewing the history of fossil-fuel consumption, the paper reviews the history of atmospheric science and the discovery of the greenhouse gas effect. This historical review aims to support the main argument in the paper concerning the basis for societal change. The need to reduce greenhouse gas emissions is then reviewed in terms of the main low-carbon energy response options.

Fossil-fuel consumption

Since around 1800, humans have rapidly increased their consumption of fossil fuels (Fig. 1a), starting with coal during the industrial revolution and then adding petroleum liquids and hydrocarbon gases, with a significant increase in the rate of use after 1950. This dramatic growth in fossil-fuel use has resulted in consumption of a very significant fraction (roughly one-third) of fossil fuel reserves, a resource which accumulated over 0.5 gyr (billion years) of the Earth's history; coals and petroleum liquids being derived from the remains of land plants and marine algae deposited and buried during the Phanerozoic Eon, a period of 541 myr. Estimates for the amount of fossil fuels consumed (Jones 2009) and the reserves remaining (Shafiee & Topal 2009) vary considerably, with a general tendency for reserve estimates to increase as new resources are discovered and developed, and as extraction technologies are improved. Recoverable reserves are also highly dependent on market prices. However, rates of consumption have started to exceed the reserve replacement rate, and human society is steadily depleting a limited and clearly non-renewable resource. For example, Shafiee & Topal (2009) argued that if the world continued to consume fossil fuels at 2006 rates, the reserves of oil, gas and coal would last a further 40,

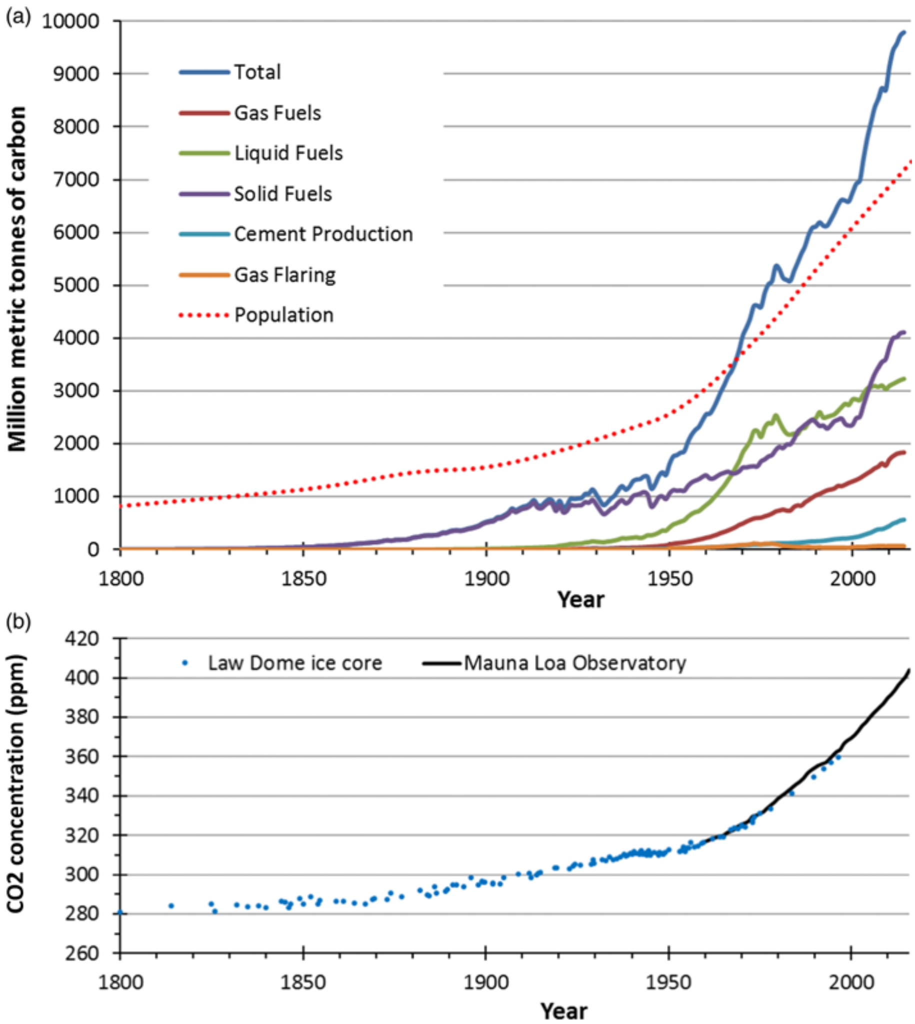

Fig. 1. (**a**) Global CO_2 emissions from fossil-fuel combustion, cement manufacture, and gas flaring and global population, 1800 – 2014 (sources: carbon emissions data from cdiac.ornl.gov, with years 2012 – 2014 based on data from BP statistical review; population data from www.census.gov). CO_2 emissions are expressed in millions of metric tonnes of carbon; to convert to the mass of CO_2 multiply by the molecular ratio 3.667. (**b**) Mean annual CO_2 concentration in the atmosphere from two sources: the Law Dome ice-core dataset (Etheridge *et al.* 1996; MacFarling Meure *et al.* 2006); and the Mauna Loa Observatory measurements from the Earth System Research Laboratory (source: www.esrl.noaa.gov/gmd/ccgg/trends/data.html).

70 and 200 years, respectively. Furthermore, arguments for limiting fossil-fuel use in order to control greenhouse gas emissions (McGlade & Ekins 2015), popularized as the unburnable carbon argument, will further constrain the actual use of these fossil-fuel reserves.

It is therefore clear that continued reliance on fossil fuel is not sustainable. This important conclusion is, however, in conflict with the current social and economic demands of that same society. Economic development of modern human society, especially since 1800, has been driven by energy from fossil fuels. Current global fossil-fuel consumption is around 82% of the world energy supply (IEA 2016*a*), with transport, manufacturing and agricultural sectors all being highly dependent on these relatively cheap and available sources of energy. During the age of fossil-fuel consumption (illustrated in Fig. 1a), the average global domestic product per capita (GDP) has grown from around 0.3% in 1820 to over 2% by 2005. Between 1900 and 2005 GDP grew by a factor of 5 and global use of materials increased by a factor of 8 (Krausmann *et al.* 2009). It is therefore equally clear that fossil fuels are currently essential for sustaining human populations and economic growth. This dichotomy is frequently overlooked in the discourse between advocates of the urgent need to change human behaviour and those wishing to maintain and sustain current social–economic structures (e.g. governments, industries).

We argue here that this dichotomy can only be resolved if there is widespread appreciation and acceptance that the future of modern human society depends on achieving a transition to low-carbon energy use. The most widely accepted model for achieving this transition is the wedge model (Pacala & Socolow 2004), whereby gradual phasing in of renewable energy sources, adoption of energy efficiency measures and application of emissions reduction technologies for fossil fuels could enable an energy transition to occur within around 50 years. To achieve that transition, societies will need to align of all three components of sustainability, specifically: (a) appreciating that the atmosphere is an essential resource; (b) achieving social acceptance on adopting new energy solutions; and (c) implementing sustainable economic models for low-carbon energy solutions.

How humans learned to understand the role of the atmosphere

Anthropogenic global warming has been very much debated over the last decade, most notably since the publication of the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) and concerning the Working Group I contribution on the scientific basis for climate change (Solomon 2007). Anthropogenic and natural contributions to climate change have also been a major focus of published research over the last decade: recently quantified by Cook *et al.* (2013), who examined the content of over 11 000 abstracts of papers addressing climate change during the period 1991 – 2011 to demonstrate a high degree of consensus on anthropogenic causes of global warming. It is not within the scope of this paper to review the nature or causes of climate change, which are thoroughly reviewed elsewhere (Stocker 2014). It is now clear that the consequences of man-induced climate change are already evident and motivating society to change its behaviour. However, the global response in reducing emissions is still rather slow. We argue here that the objective of achieving a widespread societal acceptance of the need for a transition to a global low-carbon energy mix is best achieved by explaining the importance of protecting the Earth's atmosphere. This is most simply done by recounting the history of the discovery of the greenhouse gas effect.

The French mathematician Joseph Fourier first identified that the Earth's atmosphere acts as an insulator, generating a warmer Earth surface than can be explained by solar radiation alone (Fourier 1824; translated into English by Burgess 1837). These concepts were subsequently developed and formalized in what we now refer to as the Stefan–Boltzmann law of black-body radiation, whereby the energy radiated by a black body is proportional to the forth power of the temperature of that body. Rearranging the Stefan–Boltzmann law to give the equilibrium temperature, T_{eq}, for a planet in our solar system gives:

$$T_{eq} = \left[\frac{S(1-A)}{4\sigma}\right]^{1/4} \quad (1)$$

where S is the solar constant, A is the bond albedo and σ is the Stefan–Boltzmann constant. Assuming reasonable values of $S = 1366$ W m^{-2} and $A = 0.3$ (Pollack 1979) gives an equilibrium Earth surface temperature of 255 K (−18°C). The difference between this value and the observed average surface temperature of the Earth, at around 288 K (15°C), gives an atmospheric greenhouse warming effect of 33 K. Comparing this insulating effect of the Earth's atmosphere with the much smaller effect of atmospheric warming on Mars and the much larger effect on Venus (Pollack 1979) demonstrates the underlying importance of the Earth's atmosphere to life on Earth. Biological systems on Earth have been adapted to life on this rather unique planet, and the atmosphere plays a crucial role in determining the conditions for that biosphere.

In developing the theory of black-body radiation, Josef Stefan made use of a set of careful laboratory experiments conducted by John Tyndall (1863), who was the first to demonstrate that atmospheric gases absorb 'invisible heat rays' (infrared radiation) in a non-linear manner related to the type and concentration of the gas. Tyndall showed that aqueous vapour had the largest effect but noted the contribution of several other low concentration gases. It was, however, the paper by Svante Arrhenius (1896) in which the 'greenhouse effect' of the Earth's atmosphere was first clearly established. Arrhenius postulated that selective heat absorption in the Earth's atmosphere was mainly due to aqueous vapour and carbonic acid (H_2CO_3), and that this absorption would vary with wavelength. By using infrared radiation observations of the moon (collected by Langley and co-workers at the Allegheny Observatory in Pittsburgh, published in 1890) he was able to calculate the absorption of infrared radiation by atmospheric CO_2 and water vapour. Radiation from the full moon can be assumed as a constant source, as the moon has no appreciable atmosphere and always presents the same side to planet Earth. Using Stefan's law (now the Stefan–Boltzmann law), Arrhenius formulated his greenhouse law as follows: 'Thus if the quantity of carbonic acid increases in geometric progression, the augmentation of the temperature will increase nearly in arithmetic progression': that is, the temperature increase is proportional to the log of CO_2 concentration. Expressing this mathematically, we obtain the basic Arrhenius greenhouse gas absorption law:

$$\Delta F = \alpha \ln(C/C_o) \quad (2)$$

where ΔF is the radiative forcing (W m^{-2}), C is the CO_2 concentration and C_o is a baseline or unperturbed concentration of CO_2. The constant of proportionality, the Arrhenius number, α, has the units of E_a/RT (the ratio of activation energy to thermal energy). Assuming a typical range for α (5.3–6.3), the radiative forcing effect of increasing CO_2 concentration from the pre-industrial level of 280 ppm to the present level of 400 ppm is in the range of 1.8 to 2.2 W m^{-2} (neglecting various feedback mechanisms discussed below).

Arrhenius' insight was quite remarkable for several reasons. He was able to quantify the effect of selective heat absorption in the atmosphere due to H_2O and CO_2 by ingenious use of astronomical data – removing the effects of seasonal temperature variations in order to resolve the effect of CO_2. His analysis also set the effects of different atmospheric gases in the context of the solar system as a whole. Our understanding of the greenhouse gas effect has progressed considerably since this early insight (Lashof & Ahuja 1990; Hansen *et al.* 1997; Stocker 2014) with appreciation of the need to understand the radiation and absorption effects at different levels in the atmosphere, and the feedback mechanisms associated with ocean circulation and natural carbon sinks and sources. We also know that other trace gases (principally methane, nitrous oxide, chlorofluorocarbons and ozone) have a strong greenhouse gas effect, with, for example, methane having 3.7 times the warming potential of CO_2 per mol of gas (Lashof & Ahuja 1990). Combining the radiative forcing effects of all greenhouse gas emissions from human activities gives around 1.5 W m^{-2} of additional radiative forcing in the period 1750 – 2005 (Forster *et al.* 2007), with CO_2 still having the largest effect on account of the volumes contributed. The coupling of this radiative forcing effect to temperature rise is complex and non-linear: but, in general, a radiative forcing of 0.5 – 1.3 W m^{-2} corresponds to a warming of 2 – 5°C (Lashof & Ahuja 1990). An important factor in this coupling is residence time of the various greenhouse gases in the atmosphere. Sonnemann & Grygalashvyly (2013) gave a recent assessment of the residence time for CO_2, explaining the many factors controlling the reported ranges in estimates and concluding on a mean of 130 years (for an equilibrium mixing model). The most recent estimate of the total anthropogenic radiative forcing effect for the period 1750 – 2011 is 2.29 W m^{-2}, with an uncertainty interval of 1.13–3.33 W m^{-2} (IPCC 2013).

It is also important to evaluate the greenhouse gas effect in the context of the solar system as a whole, much as Arrhenius did in 1896. The essential external control on the Earth's climate is the solar radiation intensity, which itself is strongly controlled by the Earth's orbit. The eccentricity and obliquity of the Earth's orbit and the precession of Earth's rotational axis lead to cyclic changes in the Earth–Sun distance and consequently to oscillations in solar heating, called Milankovitch cycles after the pioneering work of the geophysicist and astronomer Milutin Milanković (first published in 1913). The significance of these cycles was subsequently demonstrated by analysis of oxygen isotopes in the geological record, where the Milankovitch cycles can be clearly seen to control the climate record over the last 500 kyr (Hays *et al.* 1976) and, indeed, throughout the geological record.

The potential importance of CO_2 and its influence on the Earth's climate continued to be a matter of debate and analysis in the following decades (Callendar 1938, 1958; Revelle & Suess 1957), and then came into renewed focus following the initiative of Keeling and others (Keeling 1978), who started collecting atmospheric CO_2 concentration data at the Mauna Loa Observatory in 1958 (Fig. 1b). This programme of data collection continues under the Scripps Institution of Oceanography, supported by the United States Department of Energy, and more recently by Earth Networks in developing a global greenhouse gas monitoring network. CO_2 atmospheric measurements since 1958, along with previous CO_2 concentrations based on ice-core data over the last 800 kyr (https://scripps.ucsd.edu/programs/keelingcurve/), have been widely discussed and analysed (see Tans 2009). They demonstrate a very significant change in atmospheric CO_2 concentration (Fig. 1b) corresponding with the anthropogenic emissions of CO_2 during the industrial age (Fig. 1a).

In order to coordinate efforts to understand the effects of human-induced climate change, the Intergovernmental Panel on

Climate Change (IPCC) was set up by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) with the objective: ‘to provide the world with a clear scientific view on climate change and its potential impacts’. IPCC Assessment Reports were published in 1990, 1995, 2001, 2007 and 2013. In the IPCC (2007) Fourth Assessment Report the authors stated that:

> Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level.

The IPCC (2007) report also stated that:

> Eleven of the last twelve years (1995 – 2006) rank among the twelve warmest years in the instrumental record of global surface temperature (since 1850) [and that] most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.

Responses to these efforts by the IPCC were highly varied. The IPCC was awarded the Nobel Peace Prize in 2007 for its work on climate change. However, the IPCC (2007) report also attracted significant criticism over alleged exaggeration of the effects of human-induced climate change and over some errors identified in the report, notably concerning the claim that Himalayan glaciers could disappear by 2035. The IPCC subsequently acknowledged some specific errors but reaffirmed its main conclusions and agreed to tighten up its reviewing procedures (IPCC 2010). The Fifth IPCC Assessment Report (AR5), completed in 2013, focused on the physical science basis for climate change, with many working groups looking at different parts of the ocean–atmosphere system. The working group 1 report (Stocker *et al.* 2013) included work on better quantification of processes and causes of climate change, with special attention to the treatment of uncertainty, while the summary for policy makers (IPCC 2013) continued to emphasize significance of man-made impacts on climate, stating that: ‘It is extremely likely that human influence has been the dominant cause of warming since the mid-20th century’.

Figure 2 shows one of the summary datasets from IPCC (2013), illustrating the current understanding of the relationship between global mean surface temperature and cumulative total global CO_2 emissions. By comparing model results for the historical period (1870 – 2010) with a set of selected climate-carbon-cycle forward models up to 2100 (termed ‘Representative Concentration Pathways’ (RCPs)), the graph illustrates the potential impacts on global temperature within estimated uncertainty ranges (shaded region labelled RCP range). The historical temperature increase of around 1°C warming lies well within the uncertainty ranges and confirms, beyond reasonable doubt, that the additional greenhouse warming effect is due to anthropogenic emissions. The expected temperature rise within 2100 is between 2 and 5°C (depending on which RCP model scenario is followed), representing between 6 and 15% of the natural Earth-system greenhouse effect. See the caption to Figure 2 and IPCC (2013) for further discussion of the assumptions made and models used.

It is beyond the scope of this review to discuss the findings of the IPCC in further detail, especially as the objectives of the IPCC were to summarize and review the published works on the many topics involved. Rather, it is our goal to set this work in its historical context. The conclusions of the IPCC group of scientists are largely consistent with earlier works, including Arrhenius (1896) and, for example, Schneider (1975), who argued that global warming due to a doubling of CO_2 emissions would be in the range of 1.5 – 3°C (based on climate modelling). In recent years, using a wide range of

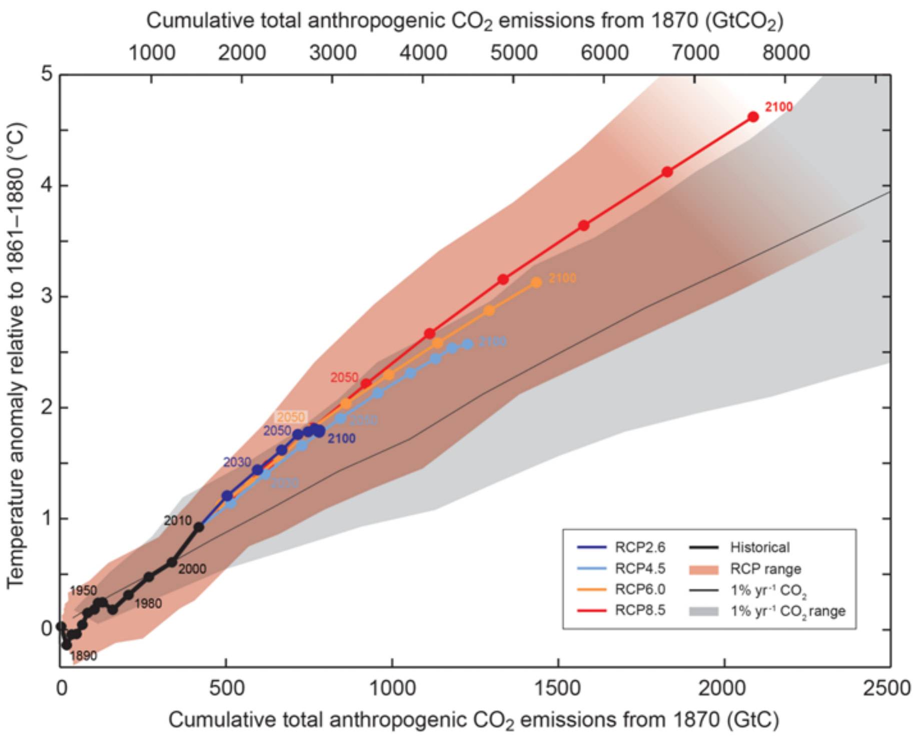

Fig. 2. Global mean surface temperature increase as a function of cumulative total global CO_2 emissions from various lines of evidence. This figure, figure SPM.10 from IPCC 2013, is reproduced with permission. Model results for the historical period (1860 – 2010) are compared with results from a hierarchy of climate-carbon-cycle forward models for a range of scenarios, termed Representative Concentration Pathways (RCP) up to 2100. Each RCP shown (RCP 2.6, 4.5, 6.0 and 8.5) is the result of a multi-model climate-carbon cycle model, with decadal means shown as dots. Decadal averages are connected by straight lines. Model results over the historical period (1860 – 2010) are indicated in black. The coloured plume illustrates the multi-model spread over the four RCP scenarios and fades with the decreasing number of available models in RCP8.5. The thin black line and grey area are a multi-model mean and range for models forced by a CO_2 increase of 1% per year (1% per year CO_2 simulations). For a specific amount of cumulative CO_2 emissions, the 1% per year CO_2 simulations exhibit lower warming than those driven by RCPs, which include additional non-CO_2 forcings. Temperature values are given relative to the 1861 – 1880 base period, while emissions are relative to 1870.

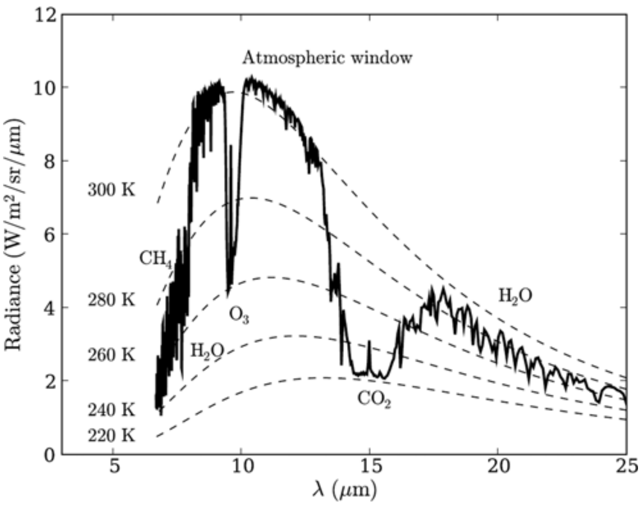

Fig. 3. Spectrum of terrestrial infrared radiation (Sportisse 2010). The spectrum is computed by the numerical model MODTRAN for the standard atmosphere (USA 1976, clear sky). The Planck black-body emission distributions are given for 220, 240, 260, 280 and 300 K. The corresponding greenhouse gases are indicated near the absorption peaks. This figure, from Sportisse (2010, fig. 2.12), is reproduced with permission © Springer.

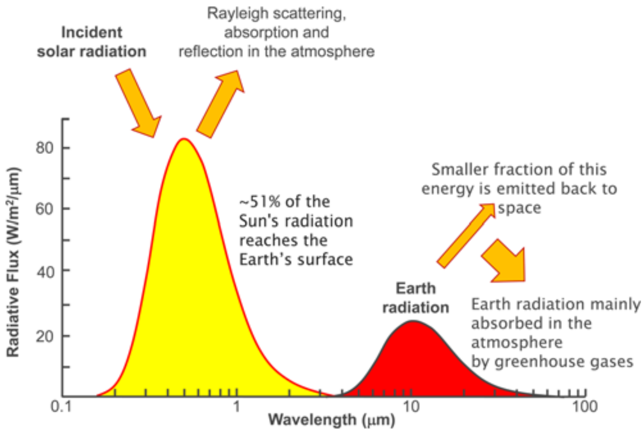

Fig. 4. Summary of radiative fluxes in the Earth's atmosphere (fluxes based on Pidwirny 2006).

land-based and satellite-based measurements, we are able to measure the greenhouse effect of CO_2 more directly, most simply by observing the spectrum of terrestrial infrared radiations from space. Figure 3 (from Sportisse 2010) shows a computed Earth radiation spectrum for a standard atmosphere as would be measured by a sensor at an altitude of 70 km. The Planck black-body emissions distributions are given for selected temperatures (in kelvins) with the corresponding greenhouse gases indicated near the absorption peaks. Put simply, the Earth with a mean surface temperature of 15°C (or 288 K) should emit radiation close to the 300 K black-body emissions curve: however, certain greenhouse gases (CH_4, O_3, CO_2, H_2O) cause significant absorption at certain wavelengths, thus causing greenhouse gas warming. The greenhouse effect has also been quantified using land-based measurements by comparing two sites over a 10 year period (Feldman *et al.* 2015).

Given this history of the discovery of the greenhouse effect as a significant factor in controlling the Earth's climate, it is, nevertheless, important to appreciate that the Earth's climate is controlled by many factors, which can be broadly summarized under three groups:

- external factors related to the solar system – Milankovitch cycles and the solar heating cycles;
- Earth-system factors – principally ocean circulation and volcanic eruptions;
- atmospheric factors – mainly the greenhouse gas effects.

Foster & Rahmstorf (2011) published a comprehensive analysis of global temperature over the last 30 years, separating out the external (exogeneous) effects from the inferred greenhouse warming effects. Their analysis showed that the El-Niño/Southern Oscillation (the dominant Pacific ocean-circulation pattern) has the largest external effect on global temperature in this period. Two volcanic eruptions (El Chichon in Mexico in 1982 and Mt Pinatubo in the Philippines in 1991) caused significant cooling for about half a year after the eruptions, but within a year the temperature recovered. The effect of the approximately 11 year solar sunspot cycle is also very clear – causing around 0.2°C variation. Their analysis illustrates how the different factors influencing the Earth's temperature can be identified and quantified, and, more importantly, separated from the effects of CO_2 emissions in the last 100 years. Concerning temperature changes over a longer period of time, Otterå *et al.* (2010) published an analysis of northern hemisphere climate changes over the last 600 years, combining instrumental data, proxy climate records and climate modelling to address longer-term changes and controls on climate. They concluded that climate fluctuations over this period are, to a large degree, governed by changes in the external factors, namely solar and volcanic climate forcing. However, by comparing models with and without the greenhouse gas forcing effects, they also concluded that external forcing cannot explain the late-twentieth-century warming. Their analysis is especially valuable as it sets the twentieth-century-modified greenhouse gas warming effects in the context of the longer-term trends and the external forcing effects.

The scientific case for the urgent need to protect our atmosphere from the damaging effect of anthropogenic emissions of greenhouse gases is now overwhelming. While discussion of the possible effects of these human-induced emissions on the Earth's climate will certainly continue, we argue here that the principle motivation for changing human behaviour should be based on appreciating the principles of atmospheric physics (summarized in Fig. 4). Since the first identification of the role of the atmosphere (Fourier 1824) in controlling the Earth's surface temperature, we have gradually developed our understanding of the critical importance of atmospheric gases in maintaining an equitable surface environment, sufficient for sustaining the human population and the biosphere on which that population depends.

The low-carbon energy transition

It follows from the preceding summary of atmospheric physics and the greenhouse effect that the current situation of high global CO_2 emissions is not sustainable. Using the framework of the Brundtland Commission on Environment and Development, human society needs to achieve transition to a set of sustainable energy solutions. Here we define sustainable energy as the exploitation of the Earth's natural resources to obtain energy without significant harm to the environment, where the environment encompasses the atmosphere, biosphere, hydrosphere and geosphere. It follows that sustainable energy solutions must also be low-carbon energy solutions. It is also important to note that renewable energy options also require exploitation of the Earth's natural resources: for example, the metals and minerals (especially those containing rare-earth elements) used in production of solar photovoltaic cells and wind turbines.

In an effort to coordinate global efforts to change human energy consumption habits, the International Energy Agency (IEA) has, since 1993, developed a series of medium- to long-term energy projections using a range of models presented annually as a set of World Energy Outlook (WEO) scenarios (www.worldenergyoutlook.org/publications). The IEA WEO team has essentially put into practice the concept of the wedge model, proposed by Pacala & Socolow (2004), in which the climate and energy problem is addressed using a pragmatic approach. The essence of their argument is that no single technology can solve the problem and that all potential low-carbon energy solutions need to be applied to the problem at the same time. This is the principle of complementarity, whereby all low-carbon energy options need to be used together to achieve the necessary reduction in greenhouse gas emissions. There is a clear consensus that this concept is the only viable solution to the climate-energy challenge and many efforts are underway to implement these actions, most recently under the terms of the Paris Agreement made at the 21st session of the Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) and the 11th session of Parties to the Kyoto Protocol, in December 2015.

Despite this general consensus on the need for low-carbon energy solutions, real progress in achieving the desired energy transition is slow and currently insufficient for meeting the objectives for emissions reductions, as stated in the Paris Agreement. The reasons for this lack of progress are complex and globally heterogeneous but grounded in the underlying principles of sustainability. Without an alignment of the environmental objectives with the economic and social factors, significant progress is unlikely. A simple example of the economic factor is the widespread reduction of subsidies for solar power in European countries following the economic recession since 2008, leading to reduced deployment rates and indicating how economic stimuli are needed to ensure continued deployment of low-carbon energy solutions. The sociological factors are illustrated both by the reluctance of fossil-fuel-dependent nations to adopt new energy solutions (Geels 2014) and by the psychological factors whereby humans tend to resist change, by saying one thing and doing another, in a form of cognitive dissonance around the climate change question (Stoknes 2015). This cognitive dissonance between the desire to address the underlying causes of climate change and the reluctance to change energy-use behaviour should eventually be resolved, but the key concern is that this change in behaviour may occur too late. Acknowledging that changing the energy system in any human society or political system is a highly complex problem (Bale *et al.* 2015), we argue here that the fundamental issue is the need for alignment of the three pillars of sustainability in developing the transition to low-carbon forms of energy (Fig. 5).

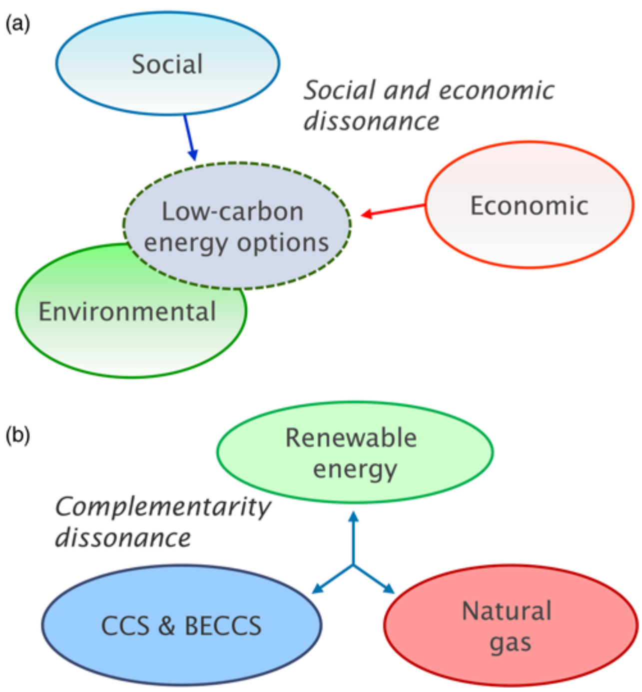

Fig. 5. Illustration of the main dissonance factors hindering adoption of low-carbon energy solutions: (**a**) the lack of social and economic support for low-carbon energy options; and (**b**) the lack of appreciation that simultaneous and complementary solutions are needed (and not just the most attractive option).

We consider three main groups of low-carbon energy:

- renewable energy options;
- natural gas (by virtue of displacing higher CO_2 emission fossil fuels);
- carbon capture and storage (CCS).

The main dissonance factors hindering adoption of low-carbon energy solutions are the lack of social and economic support for low-carbon energy options (Fig. 5a), and the lack of appreciation that simultaneous and complementary solutions are needed (Fig. 5b). Typically, a social group or nation will choose to adopt the most attractive option (e.g. switching from coal to gas or deploying new renewable energy electricity supply) and neglect other equally important actions. It should also be acknowledged that energy efficiency measures have potentially the largest overall effect on reducing global greenhouse gas emissions (IEA 2015*b*). Improving energy efficiency and reducing end-user energy demand are vital to reducing greenhouse gas emissions and are generally easily accepted by society since they give relatively quick economic benefits. However, since this factor is not very important to the cognitive dissonance issue, it is not considered further in this evaluation. The nuclear energy option is also not considered here due to its relatively smaller contribution globally, and the completely different set of environmental, social and economic factors dictating its use.

Renewable energy solutions are a vital part of the low-carbon future and, in the long term, are expected to be the dominant option. However, renewable energy options are limited by three important constraints: capacity, cost and constancy. Renewable energy sources are often grouped into two classes: new renewables (solar, wind, tidal and geothermal) and conventional renewables (including hydropower and biomass). In 2008, the total renewables contribution to global electricity generation demand was 19.8%, with new renewables contributing about 3.4% (Arent *et al.* 2011). By 2015, newly installed renewable capacity had already increased to a level able to supply an estimated 23.7% of global electricity demand, with hydropower providing about 16.6% (REN21, 2016). Certain nations have already achieved very high fractions of domestic electricity supply from renewable sources, including Zambia and Paraguay at close to 100%, Norway at 98%, Canada at 65% and Denmark at 50% (based on IEA figures for 2012). Corresponding figures for large economies include China at 21%, EU at 14% and the USA at 12.5%. Some nations have also achieved rapid increases in renewable power generation: notably, Uruguay moving from 63% in 2012 to 94.5% in 2015. In the European Union (EU) the target of achieving 20% renewable power supply by 2020 looks plausible: however, the goal of achieving 30% renewables by 2030 was recently revised down to a target of 27% by 2030, illustrating the practical limits to the share of energy that can be met by renewable energy sources. With regard to the intermittent nature of many renewable energy sources (Beaudin *et al.* 2010), significant capacity growth is only likely to be achieved in parallel with energy storage, including compressed air, electrochemical battery, hydrogen fuel cell and flywheel storage options (Ibrahim *et al.* 2008; Dunn *et al.* 2011).

In considering a range of scenarios for future renewable energy contributions, Arent *et al.* (2011) showed that the potential is between 10 and 50% of global primary energy demand, and up to 70% of total electricity generation, by 2050. This strong potential in the electricity supply sector must be balanced against the transport and heavy industry sectors, such as steel and cement production which cannot currently be powered by renewable energy sources. Biofuels as a share of transportation energy could also make significant contribution, led by the USA with a target of 20% by 2022 (Arent *et al.* 2011). Thus, the potential contribution from the renewables sector to the low-carbon energy transition is very significant but insufficient on its own. Globally, electricity generation from the renewable power sector is likely to dominate by 2050, but the total renewable energy contribution by 2050 is more likely to be closer to one-third.

Natural gas is also an important bridge to a low-carbon future, having about 30 – 50% lower CO_2 emissions per energy unit compared to coal-fired power stations (Fig. 6) (Weisser 2007; Burnham *et al.* 2011). Furthermore, switching from coal-fired electricity generation to power generation from natural gas allows very rapid reductions in a nation's greenhouse gas emissions. Global gas consumption doubled from 1980 to 2010, with consumption of dry natural gas rising from 53 trillion cubic ft (Tcf) to 113 Tcf in this period (www.eia.gov). By 2013, natural gas provided 21.4% of the world's total primary energy supply (IEA 2015*a*), and this contribution from natural gas is on a clearly increasing trend (IEA 2015*b*). Using a range of CO_2 emissions and energy use scenarios, McGlade & Ekins (2015) have argued that gas is likely to play an important role in displacing coal as a power source in both the electrical and industrial sectors (assuming the constraints of a 2°C global warming scenario). Even with this expected growth in the use of natural gas, carbon-budget limits are expected to result in a peak in global natural gas usage at some point between 2030 and 2040 (McGlade *et al.* 2014).

An important constraint to the evident attractiveness of natural gas as energy source is the concern over associated methane emissions. Natural gas production has a small but significant quantity of associated methane emissions which potentially increase their greenhouse gas footprint considerably (Howarth *et al.* 2011). Total life-time methane emissions from a typical conventional gas production well are estimated to be around 1%, and for unconventional (shale-gas) production wells closer to 3% (Howarth 2014). However, with significant efforts to further reduce these fugitive methane emissions (via monitoring and improved wellhead and gas transport practices) and to reduce the overall greenhouse gas footprint from natural gas production (Alvarez *et al.* 2012; Allen *et al.* 2013), it is clear that natural gas will play a very important role in reducing CO_2 emissions in the coming decades.

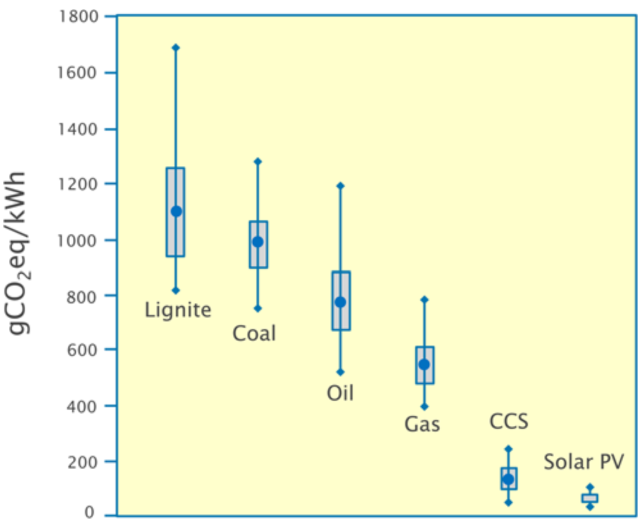

Fig. 6. Life-cycle greenhouse gas emissions for selected power plants compared with selected CCS projects for coal and gas combustion and solar photovoltaic systems (redrawn from Weisser 2007).

The third main group of low-carbon energy solutions is CO_2 capture and storage (CCS). CCS emerged as an industrial concept around 1990 (Holt & Lindeberg 1992) and was first implemented at an industrial scale at the Sleipner project in Norway in 1996 (Baklid *et al.* 1996; Eiken *et al.* 2011). CCS technologies were subsequently developed and broadened into a global solution for greenhouse gas control (Metz *et al.* 2005; Gibbins & Chalmers 2008; Haszeldine 2009). The first industrial-scale CCS projects were associated with CO_2 removal from natural gas processing, but the technology was subsequently applied to coal-fired power plants, and to ethanol, fertilizer and hydrogen production plants. In addition to reducing CO_2 emissions from fossil-fuel combustion, CCS is also the primary means of decarbonizing industrial processes, notably cement and steel manufacture. Industrial-scale application of CCS to the steel and cement industry is currently in an emerging phase, with new pilot and demonstration projects being planned. Furthermore, by combining CCS with biomass energy, the potential for negative emission technologies becomes both feasible and potentially critical for achieving significant reductions in greenhouse gas emissions (Azar *et al.* 2010; IPCC 2014; Kemper 2015). Several bio-energy CCS projects at the 1 Mtpa (million metric tonnes per annum) scale are already in operation, notably the Illinois Basin Decatur Project in the USA (Finley 2014). With 20 years of operational experience in monitoring and managing over 45 CO_2 storage projects worldwide (Pawar *et al.* 2015; IEA 2016*b*), considerable experience has been gained in understanding and managing site performance risks, forming a basis for large-scale deployment of geological storage of CO_2. Despite being a key part of the transition to a low-carbon energy mix, CCS has not experienced the same levels of growth as have occurred for renewables and natural gas. So far, monitored CCS projects have only stored 50 Mt of CO_2 in geological formations (Pawar *et al.* 2015). There has been some progress; by 2016 there were 15 large-scale CCS projects in operation and six more in construction, giving 21 large-scale projects by the end of 2017, with a collective capacity to capture and store around 40 Mtpa of CO_2 (GCCSI 2016). Considering CCS projects currently in the planning stages, this capacity could increase to 100 Mtpa by around 2030. However, a 10-fold increase beyond this level would be needed if the greenhouse gas reduction goals implied by the Paris agreement were to be realized. Most current large-scale CCS projects have capacities of around 1 Mtpa (Wright *et al.* 2009), although the Gorgon CCS project in Australia, expected to start in 2017, will have a capacity of close to 4 Mtpa.

The reasons for lack of progress with implementing CCS can be found in both the social and economic aspects of sustainable development. CCS, as a low-carbon energy option, suffers from a credibility problem as it is regarded by many as an undesirable route to continued use of fossil fuels, often associated with the un-burnable carbon argument (Leaton *et al.* 2013). Assuming a global limit to fossil-fuel combustion, McGlade & Ekins (2015) concluded that in order to meet the targets associated with a 2°C global warming scenario, one-third of oil reserves, half of gas reserves and 80% of coal reserves would need to remain unused in the period 2010 – 2050. Their estimates of useable fossil-fuel reserves were only extended by 6% in scenarios where CCS technology was applied (due to the high cost of CCS and the relatively slow rate of implementation). In the World Energy Outlook 2015 report (IEA 2015*b*), the IEA anticipates a gradually reducing contribution of fossil fuels to the global primary energy

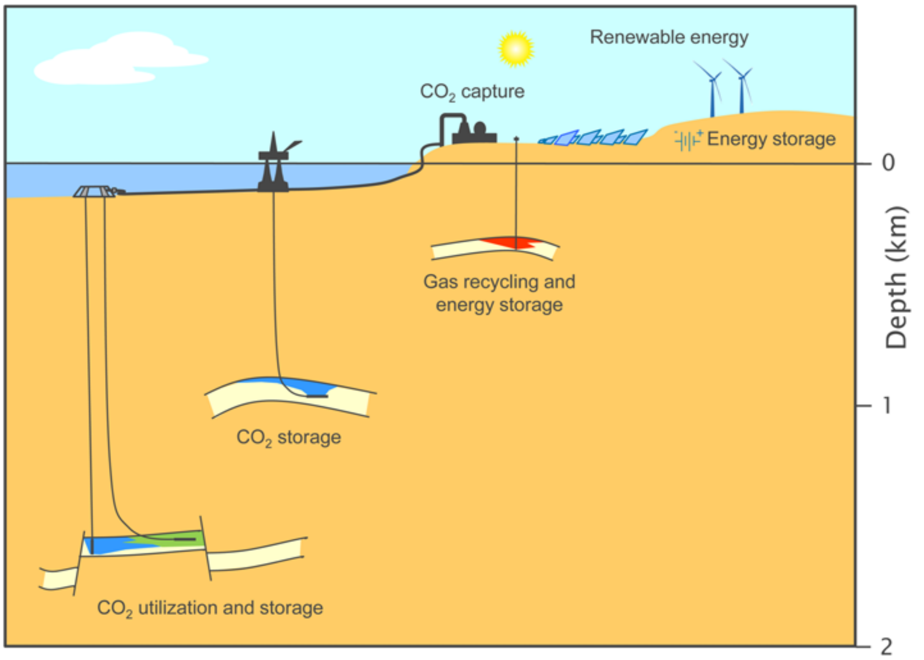

Fig. 7. Sketch illustrating deployment of integrated and complementary low-carbon energy solutions.

mix, declining from 80 to 75% in 2030, with coal and oil on a declining trend, and only natural gas increasing by around 30% during this period. This analysis is based on the current national pledges for reducing emissions (the INDC scenario), with the IEA bridge scenario involving more aggressive reductions in fossil-fuel use. The IEA analysis considers CCS to be a vital mechanism for decarbonizing both power supply and industry, with a projected mass of 52 Gt CO_2 needing to be captured between 2015 and 2040 (in their 450 ppm scenario). This would require around 2000 CCS projects, assuming a mean capacity of 25 Mt per project. Both the IEA (2016*b*) and the GCCSI (2016) outline strategies for how this scale-up might be achieved, highlighting the urgent need for investment in CCS and for policy parity with renewable energy initiatives.

The high investments cost of applying CCS is the second major reason for lack of progress. The capital cost for a new industrial CO_2 capture plant is of the order of $1000 million (USD), with operational costs in the range of 40 – 120 $/t of CO_2 emissions avoided (Gibbins & Chalmers 2008). Such projects are only viable with a CO_2 price of $50 or more, alongside policy support for the infrastructure investments. The main arguments in favour of CCS are that: (a) it is essential for achieving the greenhouse gas mitigation scenarios; and (b) that, in terms of price per tonne of CO_2 emissions avoided, CCS is competitive with renewable energy options (Sweeney 2012). The IPCC (2013) report (Stocker 2014) argued that without CCS the average cost of achieving the 2°C scenario is more than twice as high. The IEA (2015*b*) also argued that deployment of CCS would drive down the overall costs of emissions reduction and improve the competitiveness of all CO_2 abatement activities.

In order to stimulate large-scale CCS projects, a range of CO_2 capture utilization and storage (CCUS) options have been proposed. Most of these use CO_2-enhanced oil (or gas) recovery as an economic driver, whereby CO_2 is used to extract oil and then recycled and stored in the oilfield (Gozalpour *et al.* 2005). The majority of CCS projects deployed so far in the USA and Canada are integrated with CO_2 EOR, with the Weyburn–Midale Project in Canada taking the lead in terms of monitoring and research of this concept (Whittaker *et al.* 2011). CCUS could be used to accelerate and stimulate the necessary growth of large-scale CO_2 capture, transport and storage systems (Godec *et al.* 2013), and has great potential for enabling low-carbon technology growth in developing countries (Liu & Liang 2011).

Global response options

There is thus a strong case for deploying CCS in the future energy mix, if modern human society wishes to maintain current levels of economic development following its historical dependence on fossil energy. CCS is critical for achieving the necessary limits to greenhouse gas emissions and is also a very cost-effective method for achieving these goals. The key question is how to make CCS a sustainable activity, alongside the renewable and natural gas components of the low-carbon energy mix. The relatively positive social acceptance of renewable energy and natural gas options contrasts with significant social and political reluctance to deploy CCS at the scales necessary to curb greenhouse gas emissions. Switching to renewable or natural gas energy options also involves generally smaller initial capital investments than investing in new CCS projects. Implementation of carbon-pricing mechanisms and stronger regulatory frameworks will be essential for removing the economic barriers to CCS projects, but social acceptance of the need for transition to a low-carbon energy mix is equally critical. As originally outlined by Pacala & Socolow (2004) and further developed by the IPCC (2014), all low-carbon energy mechanisms are needed in parallel in order to limit harmful levels of greenhouse gas emissions to the atmosphere. These complementary low-carbon energy solutions are all currently available and ready for deployment (Fig. 7), although further cost savings, efficiency gains and more effective co-use of low-carbon energy systems remain important issues for further improvement in the many technologies involved.

How then will human society respond to this challenge? Numerous scientific institutes and international advocacy groups have presented forecasts of future energy use (e.g. IEA 2015*a*, 2016*a*), of global emissions scenarios (e.g. IPCC 2013, 2014) (Fig. 2), and of the potential impacts of these emissions on the Earth's climate and ecosystem (e.g. Ganopolski *et al.* 2016; Woosley *et al.* 2016). Whilst the detailed analyses embedded in these studies are vital to understanding the complex systems involved and for supporting strategies for mitigating the effects of greenhouse gas emissions to the atmosphere, they can lead to confusion around the key issue for human society, namely the urgent need to reduce greenhouse gas emissions. In order to address the underlying problem discussed in this review, namely the cognitive dissonance in society between energy use and the urgent

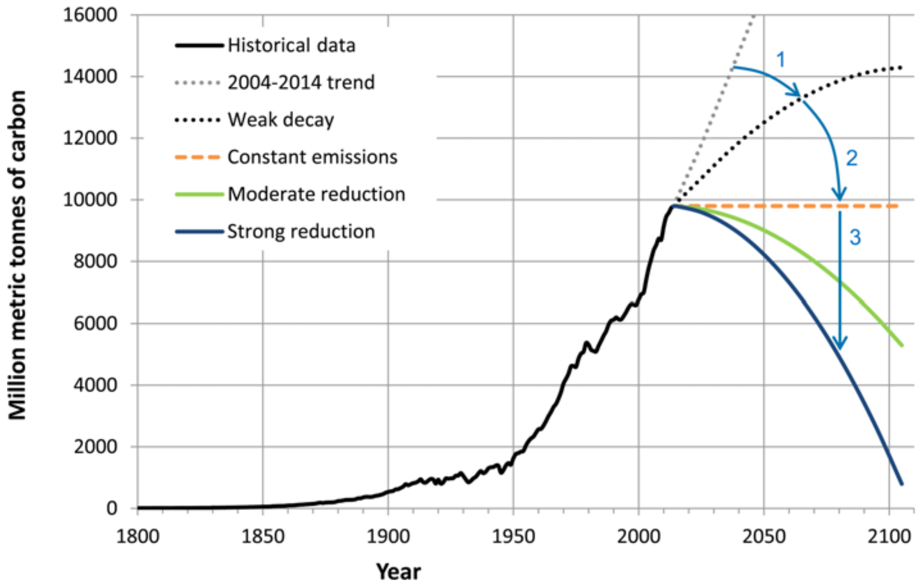

Fig. 8. History of global carbon emissions (source: cdiac.ornl.gov) compared with a set of projected curves based on various annual emissions reduction rates (Table 1). Arrows indicate wedges of emissions reduction already achieved (1), potentially underway (2) and still to be achieved (3).

need to reduce greenhouse gas emissions, we present a summary of the global response options (Fig. 8). Taking the historical record of global CO_2 emissions to atmosphere as the primary reference (Fig. 1), we postulate four simple response options (Fig. 8). Historically, annual emissions have been growing steadily, by around 200 Mt of additional carbon each year (for the decade 2004 – 2014), easing off to around 100 Mt of additional carbon each year for the last 3 years (2011 – 2014). The 2008 – 2009 global financial crisis corresponded to a short reduction (−40 Mt) in annual global emissions, but the increasing trend was quickly resumed. Available data for 2015 indicates a flattening of total emissions (Peters *et al.* 2017). In the projections shown in Figure 8, we assume a 1 Mty^{-2} decay from the 3 year (2011 – 2014) emissions growth rate of 100 Mty^{-2}, giving the projection labelled weak decay. The other functions are based on projected constant rates of emissions reduction from a zero-growth rate starting point in the year 2015 (Table 1). This graph also presents the Pacala & Socolow (2004) wedge model concept in its current context. Recent actions, including reduced use of coal and dramatic increases in wind and solar energy supply, indicate that a peak in global emissions may have already be attained (arrows 1 and 2 in Fig. 8) and that stabilization in emissions from the historical growth trend has already been achieved.

However, it also clear that significant reductions in future emissions (the moderate or strong curves in Fig. 8) can only be achieved if all low-carbon energy options continue to be deployed simultaneously (i.e. addition of new renewable energy sources, implementation of energy efficiency measures, switching from coal to gas, widespread use of CCS and use of nuclear energy). The CCS component is vital as it includes decarbonization of industrial sources of CO_2 and the use of BECCS as a negative carbon emission option. This contention is supported by many more in-depth analyses of future greenhouse gas emissions (e.g. IPCC 2014; GCCSI 2016; IEA 2016*a*, *b*; Peters *et al.* 2017). It is also important to appreciate that the Paris agreement (UNFCCC, December 2015) with the stated objectives of

> reaching a peak in greenhouse gas emissions as soon as possible [and] undertaking rapid reductions so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century

can only be achieved if society follows strong and continued emissions reductions scenarios (arrow 3 in Fig. 8). The strong reduction scenario (Fig. 8) is also broadly similar to the potential atmospheric CO_2 futures described by Tans (2009), who showed that even if such emissions reductions were to be achieved (by *c.* 2100) it takes another 500 years for the stabilization of atmospheric CO_2 concentration to occur.

Table 1. *Assumptions for the carbon emissions reduction rate curve scenarios plotted in Figure 8*

Rate function label	Initial growth rate in 2015 (Mty^{-2})	Annual carbon emissions reduction rate (Mty^{-2})	Equivalent annual reduction rate in CO_2 (Mty^{-2})
Weak decay	100	−1	−3.7
Constant	0	0	0
Moderate reduction	0	−1	−3.7
Strong reduction	0	−2	−7.3

Conclusions

Continued and unabated use of fossil fuels is clearly not sustainable both from the resource availability and the climate pollution points of view. It is also evident that fossil fuels have been, and continue to be, essential for sustaining economic growth and prosperity in modern human society. To address this dilemma, we need to appreciate that our future depends on achieving a low-carbon energy mix. Real progress with low-carbon energy solutions is slow because of the failure to align the three pillars of sustainability. While there has been good progress with the growth in the renewables and the switch to natural gas, CCS has not seen the same level of growth because this activity is not yet sufficiently attractive in terms of economic drivers and societal acceptance. A wide range of projections for future energy use, within the constraints of atmospheric protection, require that all low-carbon energy options are deployed in parallel and at increasing scale. In these scenarios, large-scale deployment of CCS is both essential and cost-effective.

To achieve this transition to a low-carbon energy mix, human societies need to apply the principles of sustainable development to energy systems. Important dissonances between the social, environmental and economic components of sustainable development need to be resolved, related to societal acceptance of new technologies and methods to overcome the economic hurdles associated with system change. Within the overall economic argument that the costs of limiting global warming are significantly lower than the costs of adapting to unmitigated global warming (Stern 2007), society urgently needs to adopt a range of complementary low-carbon energy options.

By reviewing the history of the discovery of the greenhouse gas effect over the last 200 years, we identify the essential motivation for changing human behaviour with regard to energy use: the urgent need to protect our atmosphere from the damaging effect of man-made emissions of greenhouse gases. Even though evidence for anthropogenic global warming and the associated damage to the Earth's ecosystems is overwhelming, the associated urgent need to change human behaviour in terms of energy use is hindered by socio-economic dissonances. By addressing these social–economic dissonances and by deploying all low-carbon energy options, human society could achieve the required energy transition. The global response options have been summarized as a set of annual carbon emissions reduction rate curves to illustrate the importance of deploying all available low-carbon energy options.

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