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Future energy sources and systems—Acting on climate change and energy security

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Abstract

Climate change, air quality and energy security will change the way energy is used and supplied over the next century. Supplying increasing amounts of clean and secure energy will be a challenge that will require a great deal of innovation and investment. However, this paper shows that there are visible paths to clean and secure energy. There are plenty of resource and technology options that could lead to emissions reductions in the heat, transport and electricity sector, while improving energy security. The costs of supplying energy from different options vary widely. However, several clean energy options are viable today and several others are likely to be so in the future, as technologies improve, costs are reduced, and the competitive landscape for energy technologies evolves. Tackling climate change and energy security requires the simultaneous deployment of available commercial clean technologies, demonstration and commercialisation of technologies at the advanced research, development and demonstration stage, and research into new technologies.

Keywords: Energy; Greenhouse; Security; Technology; Innovation

1. Introduction

Energy is a fundamental driver of societies' wealth and quality of life. For over a century cheap, plentiful fossil energy has been supporting the industrialisation of many countries, and the increasingly higher standards of living of their inhabitants. However, a number of separate major issues and challenges, and their concerted effects in particular, are likely to change the way energy is used and supplied over the next century.

While consciousness about environmental issues has grown, energy use continues to cause environmental degradation, including air, water and soil pollution. Rapidly developing countries, such as China, have severe environmental problems linked to the rapid increase in energy use and its supply from polluting sources and technologies. The global environmental effect of energy use, in the form of climate change, is a serious environmental threat with no easy solution, with emissions from countries already responsible for the bulk of the emissions expected to continue to grow.

In addition to these problems, a number of political (e.g. war in Iraq) and climatic (e.g. hurricane Katrina) destabilising factors, as well as constraints in supply capacity, have led to record oil prices above $70 per barrel, not far in real terms from the prices reached during the first oil shock in 1973. Sustained energy demand, uncertainty over future fossil fuel reserves, and increasing dependency on a few geopolitically unstable regions for the known reserves of oil, cause serious concerns over energy security, and are directing even greater political priority to this issue. Finally, we should not forget the 1.6 billion people without access to modern energy services.

Supplying increasing amounts of clean and secure energy will be one of the great challenges of this century that will require a great deal of innovation and investment. However, there are plenty of options that could help address the problems above. These include renewable and other low carbon electricity, alternative fuels such as biofuels and hydrogen, and the introduction of more efficient conversion technologies, such as fuel cells for different applications and running on a variety of fuels.

This paper discusses the potential evolution of the global energy system, with a focus on the first half of this century, and the options for a cleaner and more secure energy supply in different energy sectors. The paper begins with a review of the

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International Energy Agency scenarios and their implications in terms of greenhouse gas emissions and energy security; it then provides an overview of options for reducing greenhouse gas emissions, and discusses their materiality requirements for contributing towards stabilising emissions by the middle of this century and providing a more diverse and efficient energy system; this is followed by a more detailed discussion of the resource and technology options and their technical, economic and environmental potential and constraints; the paper concludes with some remarks on the policy requirements of a transition to a lower carbon and more secure energy future.

2. Energy trends

Global primary energy supply in 2003 was 10,579 Mtoe (443EJ) [1]. It is heavily reliant on fossil fuels (80%) (Fig. 1) and has increased by 75% in the last 30 years. Global electricity production is dominated by coal (40%), followed by gas (19%), nuclear and hydro (15% each). Final energy consumption is roughly equally distributed among the industrial, commercial and residential, and transport sectors. The transport sector is largely dependent on oil (95%), while the industrial and residential and commercial sectors have a more distributed final consumption amongst energy vectors. OECD countries account for about half of the global final energy consumption, but less than 20% of the population. Energy use in 2003 accounted for 25 Gt of CO_2 emissions.

Even considering a less rapid growth rate in primary energy consumption, 1.7% p.a. compared to an average 2% p.a. during the past three decades, the IEA World Energy Outlook Reference Scenario [2] estimates that world primary energy consumption will increase by 60% in the period to 2030. The world will continue being heavily reliant on fossil fuels and the demand for these fuels will grow significantly. Fossil fuels are expected to account for about 85% of the increase in primary energy supply. Two-thirds of the growth in energy is expected to come from developing countries. Nuclear energy will see an increase in capacity, mainly in Asia. Renewable energy use will continue to grow, mainly for electricity use, but its share will remain relatively low at about 6% of electricity supply. This Scenario has a number of potentially serious negative implications for

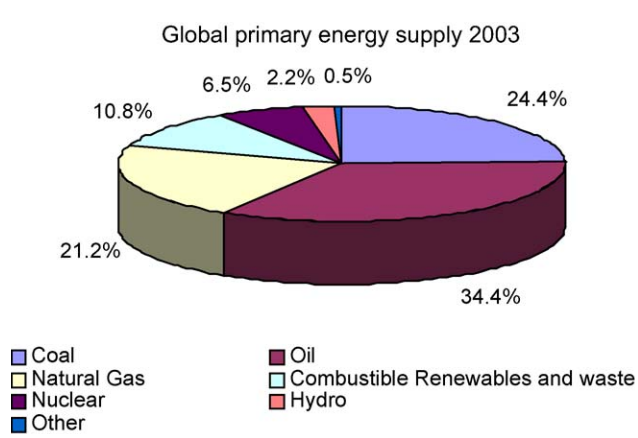

Fig. 1. Global primary energy supply in 2003.

energy security, climate change and environmental quality. Furthermore, the expected increase in energy supply will require significant investments in energy infrastructure, adding up to about $16 trillion by 2030. The externalities associated with such a scenario could be significant. The IEA WEO also presents a World Alternative Policy Scenario that depicts a more energy efficient and environmentally friendly future compared to the Reference Scenario. The Alternative Policy Scenario introduces a number of policies and measures that are currently being considered by a number of countries or that might be reasonably expected to be adopted. As a result of these measures, global primary energy demand is 10% lower than in the Reference Scenario in 2030, mainly as a result of the faster deployment of more efficient technologies. The relative reduction in fossil fuel demand and CO_2 emissions is greater than that for primary energy demand, because of the contribution of more efficient vehicles, fuel switching from coal to gas in the power sector and a shift in the power generation fuel mix in favour of renewables and nuclear energy. The CO_2 emissions are expected to be 16% lower compared to the Reference Scenario. The investment required in this scenario is higher than for the Reference Scenario, with a shift in investment from the supply side to the end user.

The IEA scenarios imply that important changes are required to address questions of local and global environmental pollution and energy security. These changes are dependent on changes and innovation in technologies, policies and consumer behaviour.

3. Future energy—reacting to environmental pollution and energy security

The stabilisation of CO_2 concentrations to a level of about 500 ppm is thought to be necessary to avoid significant damages from anthropogenic interference with the climate system. To stabilise CO_2 concentrations at this level requires that emissions be held at the present level of 7 billion GtC per year over the next 50 years, and decline thereafter. This poses an enormous challenge given that annual global CO_2 emissions are expected to double over the period to 2050 under a business-as-usual scenario. Furthermore, levels below 500 ppm may need to be achieved to avoid significant damage from climate change. So, even stronger action may be required with regard to CO_2 emissions [3].

Emissions reductions can be achieved through reduced energy demand, energy efficiency and low carbon energy supply (Fig. 2).

Pacala and Socolow [3] and Hoffert [4] discuss the importance of technological and resource transitions in stabilising and reducing CO_2 emissions over the next century. Pacala and Socolow [3] state that stabilisation of emissions over the next 50 years could be achieved with current available technologies, while emissions reductions thereafter may require major technological advances or behavioural change. Therefore, investment in research and development related to new energy technologies should be a priority today. They conceptualise carbon reductions over the next 50 years as a series of seven triangular "wedges" achieving each a reduction of 1 GtC $year^{-1}$ in 50 years time,

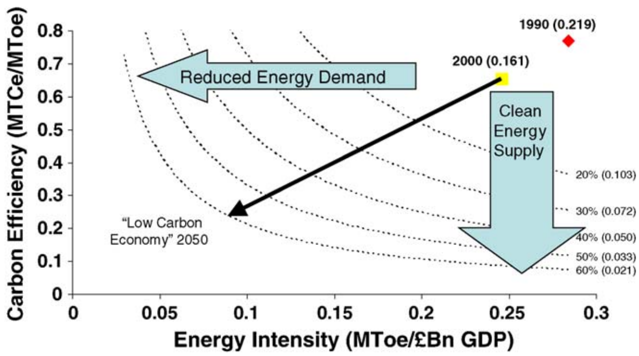

Fig. 2. Isoquants of increasing energy efficiency and decarbonising supplies. The dotted lines show possible combinations of changes in energy intensity and decarbonisation of supplies that would deliver different percentage CO_2 reductions in emissions from 2000 levels, together with (in brackets) corresponding changes in carbon intensity (C/GDP) for projected GDP growth by 2050, using example of the UK which has adopted a goal of 60% absolute reductions. The points at top right show the positions for 1990 and 2000.

based on an average carbon emissions growth of 1.5% under a business-as-usual scenario. The cumulative emissions reduction from all seven wedges over that period would be 25 GtC. Wedges could be achieved through three main categories of options: (i) energy efficiency and conservation; (ii) decarbonisation of the supply of electricity and fuels; and (iii) biological storage in forests and soils (Fig. 3).

Efficiency improvements could go a long way in helping stabilise emissions and reducing the scale of the task associated with energy supply. They depend on a wide range of innovations in energy supply and in stationary and transport end uses. As an indication, doubling the average fuel economy of vehicles over the next 50 years could contribute one of the emissions reduction wedges. Similarly, another wedge could result from the doubling of the average fossil-based electricity production efficiency from around 30% to around 60%. Energy conservation through behavioural changes, e.g. modal shifts in transport, less travel, smaller vehicles, could also provide an important contribution to the stabilisation of emissions. Energy efficiency and conservation are an essential component in reducing emissions and using resources efficiently over the long term. Given

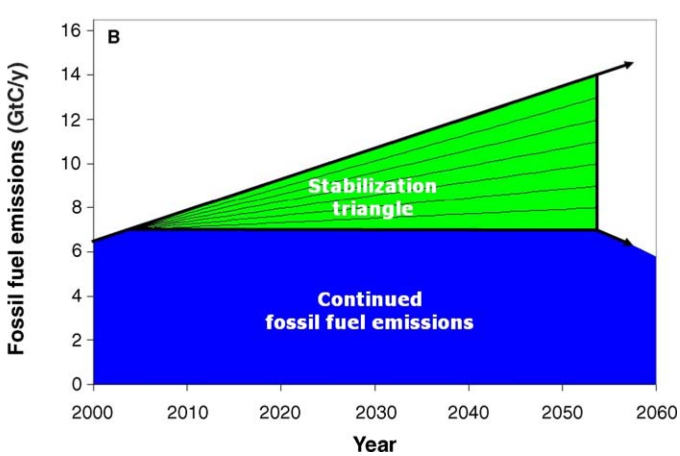

Fig. 3. The "wedges" approach to climate stabilisation.

that most growth in demand will be experienced in developing countries, programmes aimed at the transfer of energy efficiency measures and technologies to developing countries could have massive benefits.

There are many options for decarbonising the supply of electricity and fuels. Decarbonisation can be achieved through the switch to lower carbon fossil fuels (e.g. switch from coal to gas) or nuclear fuels, the sequestration of carbon produced during the conversion of fossil fuels, and the use of renewable resources.

Using nuclear power to achieve a wedge of emissions reductions would require 1400 or 700 GW of installed capacity depending on whether it is displacing natural gas or coal, respectively. This corresponds to 2–4 times current installed capacity.

Post-combustion carbon capture and storage (CCS) would need to be applied to about 800 GW of baseload coal plants to achieve a wedge of emissions reductions. Similarly, a wedge of emissions reduction could be obtained by pre-combustion CCS at coal plants producing 250 Mt of hydrogen per year, equivalent to about six times the current rate of hydrogen production. In the case of synthetic fuel production from coal, a wedge of emissions reductions could be obtained by applying CCS to coal synfuels plants producing 30 million barrels of synfuels per day, equivalent to about 200 Sasol-scale coal-to-synfuels plants.

Renewable electricity can be used to displace fossil fuels. A wedge of emissions reductions from renewable electricity would require about 2000 GW of installed wind or solar electricity capacity. Today's installed wind and solar capacity is about 40 and 7 GW, respectively. Achieving 2000 GW installed capacity implies an average growth rate of 8% for wind over the next 50 years and 12% for solar. Renewable electricity can also be used to produce hydrogen from water. It is estimated that 4000 GW of renewable electricity would be required to achieve a wedge of emissions reduction in the transport sector through the displacement of fossil-fuelled internal combustion engines with hydrogen fuel cell vehicles. This corresponds to about 2 billion vehicles, which may require converting all light duty vehicles to hydrogen by the middle of this century [5].

Biofuels are another potentially important contributor to carbon emissions reductions in the transport sector. A range of fuels can be produced from biomass for use in the transport sector. Bioethanol and biodiesel are the most common biofuels used as gasoline and diesel substitutes, respectively. If biofuels are assumed to be carbon neutral, indicatively 34 million barrels per day of ethanol, roughly 50 times today's global production, would be required to achieve a wedge of emissions reductions. An average growth rate in biofuel production of 8% would be required over the next 50 years.

However, available technological solutions and foreseen regulation may not be enough to solve the climate problem. Hoffert et al. [4] claim that more radical solutions are needed, and suggest increased efforts in pursuing the development of options such as space solar power (SSP), nuclear fusion and fission–fusion hybrids. The main advantages of these technologies would be to increase the potential supply of energy from solar and nuclear resources. Given the scale of the climate problem human society may be faced with, Hoffert et al. [4] suggest that it would also be prudent to pursue geoengineering solutions to climate change i.e. altering the planetary radiation balance to counteract the anthropogenic greenhouse gas effect. These consist mainly of solutions aimed at reducing the amount solar radiation entering the Earth's atmosphere.

The other major issue associated with energy supply is energy security, which can be defined as a reliable and adequate supply of energy at reasonable prices. OECD countries' energy imports are on the rise, in particular European countries' energy dependency on imports is expected to rise from 50 to 70% over the period to 2030. Like environmental impacts, energy insecurity too results in externalities. Considering that energy is a necessary input to all activities of a modern society, major breakdowns in the energy delivery system can have severe economic and social implications. However, disruption can also be caused by deliberate interruptions (or simply threats of interruptions) of supplies from producing countries. Energy insecurity therefore can also be described as the level of risk of a physical, real or perceived, supply disruption. The market reaction to possible future disruptions would be a sudden increase in energy price over the expected period of impact of the disruption. This would then cause inflation which in turn affects the performance of the economic system and eventually results in losses in GNP and other effects such as higher unemployment rates. A prolonged period of high and unstable prices is a typical symptom of a high level of insecurity. The market alone may not be capable of producing an optimal level of energy security for the society, so public policy intervention is likely to be required.

Improving energy security requires addressing short and long-term energy insecurity. The establishment of strategic oil reserves has helped mitigate short-term energy insecurity related to oil imports, but the gas sector remains more vulnerable to short-term insecurity. Long-term insecurity, related to the progressive depletion of resources and their geographic concentration, as well as political instability in those areas, cannot be dealt with by strategic reserves, and requires strong action in relation to demand management, technological innovation, reliance on domestic resources and diversification of sources of supply and their origin. Actions in these areas will have an increasingly positive impact on short-term energy security.

Demand management, including the introduction of new more energy efficient technologies, and increasing the share of renewable energy are two key elements of a European Union strategy for improving energy security. However, questions over the rate of introduction and potential of renewable energy sources are leading countries to (re)consider the role of nuclear and coal, possibly with CCS, for electricity generation. Also, the heat and transport sectors are the most vulnerable to energy insecurity, as they are generally entirely dependent on oil and gas. These are the sectors in which demand management and diversification face the greatest challenges.

There may be synergies between actions aimed at reducing CO_2 emissions and improving energy security. A policy aimed at reducing CO_2 emissions is expected to have positive implications for security of supply [6], as it is likely to promote a more efficient and diverse use of resources. Also, the stronger the GHG policy the more positive the effect on security of supply is likely to be. However, concerns over security of gas supply, need to be considered carefully, as these may increase with time as a result of fuel switching driven by GHG policies and scarcity of oil. Conversely, policies aimed at security of supply need not have positive implications for GHG reductions.

Low carbon policies could result in additional benefits, besides energy security, such as reduced foreign expenditure resulting from reduced energy imports (which would allow to recoup low carbon demand and supply side public investments), improved air quality, and competitive advantage resulting from a more energy efficient economy and the development of innovative low carbon technologies for export.

4. Transitions to future energy sources and systems

There are plentiful of demand and supply options for addressing climate change and energy security issues. However, the extent to which these will be adopted will depend on different drivers and constraints. No single option will provide a solution to all energy problems, but solutions will consist of a range of options that will evolve over time.

The main drivers behind change in the energy sector are climate change, air quality and energy security. The priority of these drivers is likely to vary geographically and with time. The changes instigated will be constrained by technical, economic, infrastructure, geographic and socio-political factors. Managing transitions in resources, technologies and end uses will be crucial in effectively addressing the problems facing energy supply and end use.

4.1. Heat and electricity

Coal, oil and natural gas are the main fuels used for heating, with natural gas increasingly used for heating in the commercial and domestic sectors. While the direct use of fuels for heating is generally efficient (efficiencies of modern heating systems easily exceed 80%), there are different ways in which emission savings can be achieved. Energy savings can be achieved through the diffusion of more efficient heating appliances, e.g. condensing boilers, and through more energy efficient buildings. The use of combined heat and power plants result in energy savings compared to heat only and electricity only systems providing the same service. In particular, fuel cells present emissions benefits compared to alternatives (Fig. 4). Finally, renewable sources such as biomass and solar energy could substitute fossil fuels in many heat applications [7].

Heating is possibly where the lowest cost CO_2 emissions reductions can be achieved, through efficiency measures and fuel substitution. CO_2 abatement costs could be very low and even negative when using efficiency measures and substituting wood chips and pellets or natural gas for higher carbon content fossil fuels.

The electricity sector presents a wide range of options for reducing carbon emissions. For countries where the sector has been reliant on coal, a switch to gas provides a relatively low cost route to reducing emissions. However, rising gas prices and concerns over security of gas supplies could act increasingly as a constraint on the share of gas used for electricity.

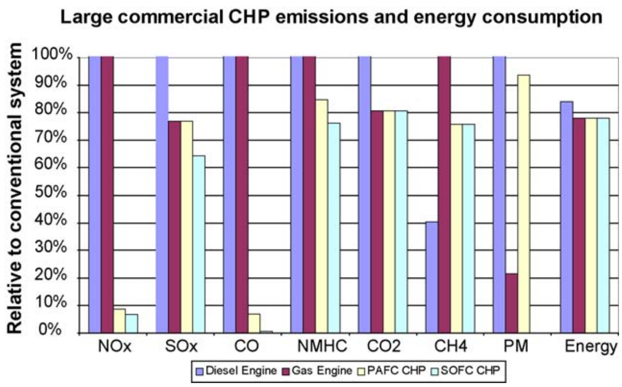

Fig. 4. Total systems emissions and primary energy use linked to large commercial CHP [8]. The conventional system consists of a mix of grid electricity from natural gas combined cycle gas turbine plant and heat from on site natural gas boilers.

Efficiency gains can play an important role in electricity generation. For example, combined cycles with natural gas (CCGT) or coal gasification (IGCC) could increase generation efficiencies to 65% (gas) and 55% (coal) by 2020 [9,10]. Also, fuel cells could provide efficiency gains in decentralised generation applications compared to engines and turbines. System efficiencies will depend on the fuel used, fuel cell type and its potential integration with other devices such as micro-turbines. For example, the electrical efficiency of a solid oxide fuel cell (SOFC) system fuelled with natural gas is estimated at 55% and that of a SOFC coupled with a small gas turbine is estimated at 70% [8]. However, fuel cell technology requires further development, demonstration and cost reductions. Fig. 5 provides an indication of cost reductions that could be achieved by fuel cell technologies as a function of their cumulative introduction (assuming a 15% learning rate).

Nuclear represents an important share of global electricity generation (16%), and provides a low carbon option for substituting fossil fuels in centralised generation systems. Nuclear fuels could contribute large CO_2 emissions reductions in the electricity sector, but significant nuclear expansion requires a solution to the problems of radioactive waste disposal and nuclear proliferation, and the restoration of public confidence in the technology.

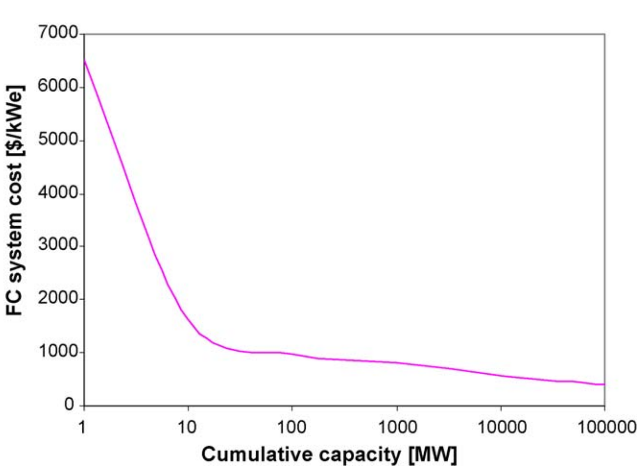

Fig. 5. Fuel cell system cost reduction curve (indicative).

The costs and liabilities of nuclear energy are high, and interest from utilities and private investors to develop nuclear plants has been low, especially in increasingly liberalised energy markets [11,12]. There is also indication that nuclear resources for fission reactors may be limited, and so nuclear fission could only provide a temporary low carbon solution, possibly expected to become exhausted during this century [4].

Carbon capture and storage (CCS) can be applied post-combustion of the fuel, where fossil fuel is used in combustion systems to generate electricity, or pre-combustion, where the fossil fuel is used to produce a lower carbon content synfuel or decarbonised hydrogen. The cost of carbon capture and storage is estimated at \$40–\$60 t^{-1} CO_2 (depending on the type of plant and where the CO_2 is stored) and estimated to contribute around \$0.015 $kW^{-1}\,h^{-1}$ to the price of electricity [13]. In addition, the generating efficiency would be reduced by 10–15% points (e.g. from 55% to 40–45%) based on current technology. Global CO_2 storage capacity in coal basins, oil and gas fields and aquifers is estimated at about 10,500 Gt CO_2, with over 90% of the storage capacity estimated to be in onshore and offshore aquifers [14]. At current rates of emissions from fossil fuel plants, it represents a CO_2 storage capacity of about 400 years. However, the exploitation of only a fraction of the storage capacity is likely to be viable. If viable, CCS could provide a means of prolonging the use of fossil fuels in a CO_2 constrained world.

Renewables have benefited the most from the limited drive to produce cleaner energy and desire to increase reliance on domestic energy sources. Significant cost improvements have been made in wind, biomass and solar electricity as a result of technological improvements and increased penetration rates [15,16], and costs are continuing to decrease. Marine technologies hold good technical promise but are still at the demonstration stage [16].

Renewables are at present the only truly sustainable source of energy. However, their contribution to electricity generation remains low, except for hydroelectricity in some countries. This is due to the generally higher costs of renewable electricity compared to conventional grid-based generation and difficulties resulting from its smaller scale and more decentralised nature [16]. Although estimates of the exploitable renewable energy potential may vary, most studies concur that it is very large (the technical potential being many times larger than current primary energy supply), in particular when the diversity of renewable options is considered [17]. Renewables are also likely to be the route to sustainable hydrogen, and hydrogen could act as a valuable means of storing intermittent renewable electricity. The interest and value, in terms of carbon abatement in particular, of using renewables to produce hydrogen should grow as low carbon sources of energy are more widely adopted for electricity generation [18].

There is a diversity of very low carbon options that have medium-term projected costs broadly around 5 USc $kW^{-1}\,h^{-1}$ (Table 1). Therefore, a very low carbon electricity future is possible with available technologies and it need not be more costly [19]. The choice of resources and technologies would vary from region to region, and the potential for diversity (combined with improving storage and grid management technologies over

Table 1
Current- and medium-term costs of electricity generation [20]

Technology	Current cost (UScents kW^{-1} h^{-1})	Medium-term projections (UScents kW^{-1} h^{-1})	Comments
Present fossil fuel plant			
Gas CCGT	3–4	Depends on fuel prices and carbon cap/price	
Coal	3.5–4.5		
Low carbon electricity technologies			
Carbon capture and storage (CCS)			Costs based on engineering assessment, as yet no market experience to permit learning rate derivation. The techniques are well known but not tested for this application
Natural gas with CCS	NA	4–6	
IGCC coal with CCS	NA	5–8	
Nuclear power	5–7	4–8	Considerable disagreement over prospective future costs. Industry provides very low cost estimates. Low historical learning rate
Biomass			
Co-firing with coal	2.5–5	2.5–5	
Electricity	5–15	5–9	
CHP-mode	6–15	5–12	
Wind electricity			Learning curve evidence and strong market growth (30% p.a.), with good engineering data allows robust assessment for onshore. Offshore less certain as experience is limited, but engineering assessment, learning rate extension/proxy indicates strong potential
onshore	5–8	2–5	
offshore	9–12	3–8	
Tidal stream/wave	13–20	8–13	Future costs difficult to estimate due to immaturity of technologies. Estimates draw on parametric models of hypothetical costs. Uncertainties are large for these technologies
Grid connected PV			Robust learning curve evidence and strong market growth (25% p.a.) suggest costs should decline strongly to 2020 and beyond. Recent cost reduction trends appear to have declined, unclear as to whether this is temporary (price increase due to high demand) or result of reduction in learning rate for particular technologies
1000 kW h m^{-2} $year^{-1}$ (temperate)	40–80	15–25	
2500 kW h m^{-2} $year^{-1}$ (tropics)	15–40	5–15	

Notes: The table shows typical busbar generating costs and medium-term (generally 2020/2025) cost projections for low carbon generation. All costs inflated from time of study to 2005, and converted at purchasing power parity rates. Cost projection methodologies in the studies are diverse. PV costs neglects offset costs (e.g. building materials displaced by PV façade). Sources: [12,13,17,21–31].

time) suggests intermittency is not a serious obstacle.The costs of CO_2 abatement vary widely for different electricity generation options compared to fossil baselines. They could range from around \$10 t^{-1} CO_2 saved for onshore wind compared to electricity from gas to over \$200 t^{-1} CO_2 for photovoltaic electricity.[1]

4.2. Transport

Transport is heavily reliant on oil and accounts for most of the projected CO_2 emissions growth in industrialised countries. Vehicle efficiency improvements and vehicle standards have provided and will continue to provide important emissions reductions per unit distance travelled [32]. Average vehicle fuel efficiency could double compared to current values, and assuring that technical efficiency improvements are converted into fuel economy gains, and not offset by increased power and size, represents an important policy challenge. Nevertheless, atmospheric stabilisation of CO_2 will ultimately require transport fuels with near-zero 'well-to-wheels' CO_2 emissions [33]. The options are biofuels, electricity, and hydrogen, the last two only helping if produced from very low net CO_2 energy sources.

Ethanol and biodiesel are already produced commercially in some countries and blended with petrol and diesel, respectively. They provide only a small fraction of transport fuels in most countries where they are used, with the notable exception of Brazil where bioethanol represents around 40% of road transport fuel in gasoline vehicles. However, biofuels are not strictly carbon neutral, and the carbon emissions from biofuel chains can vary significantly depending on the biomass feedstock and conversion process, and related materials and fuel inputs. For example, the associated CO_2 reductions compared

[1] This value does not account for any costs savings that might occur from building integrated PV.

Table 2
Current- and medium-term costs of biofuels production [20]

Technology	Current costs (UScents l^{-1}) [$ GJ^{-1}]	2020 Projections (UScents l^{-1}) [$ GJ^{-1}]	Comments
Gasoline/(diesel) cost for oil crude at ca. $50 per barrel (FOB Gulf cost)	0.34/(0.37), [10.4/(10.0)]	Dependent upon oil supplies	
Ethanol from sugar cane (Brazil)	0.29, [13.5]		Commercial ethanol production in Southern Brazil. Varies with exchange rate—value provided based on 2R$/US$. Some scope for cost reduction
Ethanol from corn (US)	0.29–0.32, [13.5–14.9]		Commercial ethanol production in US. Some scope for cost reduction
Ethanol from grain (UK)[a]	0.38–0.65, [18.0–30.6]		Commercial ethanol production in UK. Some scope for cost reduction
Ethanol from cellulosic crops (UK)[a]		0.31–0.73, [14.4–34.2]	Cost projection for commercial plant based on engineering analysis
Biodiesel from rapeseed (UK)[a]	0.59–1.48, [18.0–45.0]		Commercial biodiesel production in UK. Some scope for cost reduction
F-T diesel from coppice (UK)[a]		0.58–0.97, [16.2–27.0]	Cost projection for commercial plant based on engineering analysis

Sources: [34,37,38].
[a] Based in US$1.8 per £ exchange rate. Higher end of the range assumes no co-product value.

to gasoline and diesel are only about 20–50% for ethanol produced from grains, 40–60% for biodiesel from rapeseed, but up to 90% for ethanol from sugarcane in Brazil, largely because bagasse is used for process energy [34,35]. Cost reductions associated with the build-up of the Brazilian industry have made its ethanol competitive, on a volume basis, at oil prices above US$40 per barrel (though this may vary significantly depending on exchange rates) [36]. Table 2 provides an indication of current and projected biofuels production costs.

Methods that produce ethanol and synthetic diesel from lignocellulosic materials (e.g. grasses and wood) would expand the accessible resource base, improve biofuel yields per unit of land used, and possibly reduce the costs of producing biofuels, especially if low cost feedstocks can be used. Furthermore, these production routes should result in very low "well-to-wheels" emissions [37,38].

Most regions are likely to have a significant potential for biofuels production, including temperate regions like Europe [39]. There could also be a significant potential for biofuels trade. However, although biofuels could make a material contribution to transport fuels, questions remain as to the amount of biofuels that could be sustainably produced, taking into account ecological and social constraints. Also, competition between different uses of biomass for energy and materials needs consideration.

Electric and plug-in hybrid vehicles can reduce CO_2 emissions if the electricity is drawn from CCGT or lower carbon sources. The prospects for pure electric vehicles appear to be limited as a result of unsatisfactory ranges provided by batteries between recharges and inconvenience associated with recharge times. The prospects appear much more interesting for hybrid vehicles, which are being heavily invested in by car manufacturers.

Fuel cell vehicles fuelled with hydrogen from a variety of sources could provide significant CO_2 reductions and zero tailpipe emission. The CO_2 emissions reductions strongly depend on the source of hydrogen. Fuel cell vehicles fuelled with hydrogen from natural gas without sequestration could result in marginal benefits compared with advanced gasoline or diesel hybrid vehicle designs. But, hydrogen from fossil fuels with sequestration, nuclear energy and renewables offers the potential for very low "well-to-wheels" pollutant emissions. Fig. 6 gives an indication of the energy and environmental performance of fossil-fuelled fuel cell vehicles compared to alternatives.

An evolutionary route towards sustainable hydrogen might start with the use of surplus hydrogen produced at chemical or petrochemical sites, as well as local electrolysis or reformation of methane at filling stations. Initially hydrogen might be directed at the refuelling of fleet vehicles and gradually expand to other uses. Decentralised hydrogen production could, in the long term, co-exist with centralised larger scale production based on fossil (with sequestration), nuclear and renewable energy. Hydrogen production costs vary significantly depending on the source, and could be as low as $8 GJ^{-1} from large-scale natural gas reformers. However, the development of a hydrogen distribution and refuelling infrastructure will add significantly to the cost of the hydrogen delivered to the vehicles. For example, distribution and dispensing costs could double the cost of the

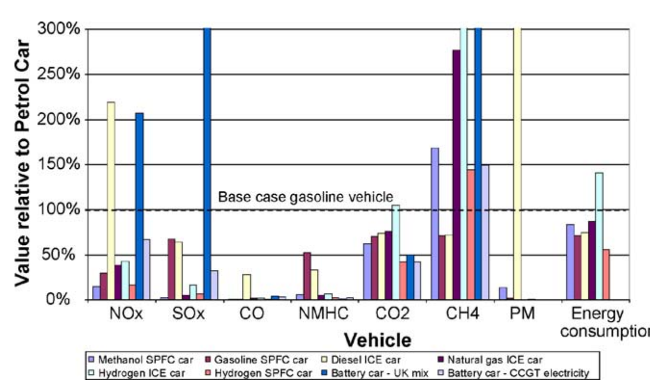

Fig. 6. Total systems emissions and primary energy use linked to passenger cars. Hydrogen is derived from natural gas reforming [8].

hydrogen produced from large-scale reforming of natural gas [40]. Hydrogen from low carbon sources is costly, so the economic viability of low carbon transport using fuel cell vehicles depends on the ability to deliver high efficiency and low cost fuel cell vehicles. The costs of carbon abatement in the road transport sector are generally higher than those that can be achieved in the heating and electricity sectors. Hybrid vehicles and biofuels could provide carbon savings at costs starting at around $\$100\,t^{-1}\,CO_2$.

However, reducing CO_2 emissions over the long term requires tackling the transport sector. While the focus has been on road transport, emissions from marine transport and aviation will also need to be tackled. Anderson et al. [41] indicate that the EU25's aviation sector could account for almost 40% of the total permissible emissions for all sectors in 2050 under a 550 ppm regime, or as much as 80% under a 450 ppm regime. Both continuous innovation in vehicle efficiency and low carbon fuels are required to assist a long-term transition to low carbon road transport. Hydrogen fuel cell vehicles appear as the long-term solution, and their development and deployment should be a short-term priority. Vehicles fuelled with biofuels, low carbon electricity, and hydrogen could all co-exist in a long-term transition to low-carbon transport. The need to make a transition in transport fuels is also driven by oil resource and supply security considerations. Compared to the century–timescale of the climate problem, global oil production will peak soon. Indeed, total remaining estimated conventional oil resources contain about a quarter of the total carbon that would have to be emitted to reach 500 ppm CO_2 [42]. The key will be to ensure that future investments are directed to lower carbon energy systems.

Spending on alternative and innovative energy technologies and fuels has been intrinsically limited by the limited scope for product differentiation in the energy sector. This is because consumers are ultimately interested in the services provided by energy e.g. mobility, lighting, heating. Also, the energy sector is generally characterised by long innovation lead times and slow technology diffusion. As a result, the share of sales revenue spent on innovation less than 0.5%, which is very low compared to other sectors, e.g. telecommunications, information technology, pharmaceuticals, where spending is over 10% of sales revenue [43].

Many promising low carbon technologies are at the pilot and demonstration stage e.g. fuel cells, hydrogen technologies, new biofuel production technologies. These technologies require a virtuous cycle of development, demonstration and market experience that will lead to their commercialisation and competitiveness with conventional fossil-based technologies. Learning incentives need to be directed to these technologies that will enable them to move along the experience curve and achieve cost reductions [15]. However, innovation in the energy sector needs to recognise that the evolution of technologies is intrinsically linked with the evolution of the institutional aspects that regulate the energy sector e.g. technical, market and environmental regulations in the electricity sector. Also, it needs to recognise the long timescales that may be involved in displacing or building energy infrastructure e.g. in the case of the development of a hydrogen infrastructure.

5. Making the transition happen

There are visible paths to low carbon and more secure energy systems, with both short and long-term options for emissions reductions and improved energy security in the heat, electricity and transport sectors.

Tackling climate change requires the simultaneous deployment of available commercial low carbon technologies, demonstration and commercialisation of technologies at the advanced research, development and demonstration stage, and research into new low carbon technologies. Innovation in the energy sector needs to recognise that the evolution of technologies is intrinsically linked with the evolution of the institutional aspects that regulate the energy sector i.e. technical, market and environmental regulations. Also, it needs to recognise the timescales and effort that are required in replacing or building energy infrastructure e.g. in the case of the development of a hydrogen infrastructure.

Achieving low concentrations of CO_2 in the atmosphere over the next century could also require changes in consumer behaviour. For example, ever increasing demand for larger and more powerful vehicles and for air travel may offset gains achieved by low carbon technology and fuels, besides exerting increasing pressure on finite energy resources and ecological capacity.

There are potentially strong synergies between tackling climate change and improving energy security, which should be considered in policy-making. Policy mechanisms are needed that stimulate innovation and provide supply and demand-side incentives to reduce CO_2 emissions, while improving energy security, across a wide range of sectors. Governments need to send strong signals about the importance of climate change and energy security in making energy supply and demand decisions.

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