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Review

# Needs, resources and climate change: Clean and efficient conversion technologies

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## ABSTRACT

Energy "powers" our life, and energy consumption correlates strongly with our standards of living. The developed world has become accustomed to cheap and plentiful supplies. Recently, more of the developing world populations are striving for the same, and taking steps towards securing their future energy needs. Competition over limited supplies of conventional fossil fuel resources is intensifying, and more challenging environmental problems are springing up, especially related to carbon dioxide ($CO_2$) emissions. There is strong evidence that atmospheric $CO_2$ concentration is well correlated with the average global temperature. Moreover, model predictions indicate that the century-old observed trend of rising temperatures could accelerate as carbon dioxide concentration continues to rise. Given the potential danger of such a scenario, it is suggested that steps be taken to curb energy-related $CO_2$ emissions through a number of technological solutions, which are to be implemented in a timely fashion. These solutions include a substantial improvement in energy conversion and utilization efficiencies, carbon capture and sequestration, and expanding the use of nuclear energy and renewable sources. Some of these technologies already exist, but are not deployed at sufficiently large scale. Others are under development, and some are at or near the conceptual state.

**Contents**

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## 1. Introduction

Energy is one of the most challenging needs of humanity, and is highest on the list of priorities and requisites for human welfare. Through rapid industrialization and the implementation of modern economic systems, food production has expanded at the expense of growing energy consumption in agriculture, transportation and processing. Similarly, providing clean potable water is an energy intensive enterprise, and can only be secured when energy resources are available. Mobility, lighting and communications are all indispensables energy intensive needs of modern life, as well as heating and air conditioning. Industrial production continues to be a large consumer of energy, in many forms, and industrialization comes at the cost of accelerated use of energy.

Energy, in its raw form, is a natural resource that exists in abundance. However, raw forms of energy are not necessarily compatible with the functions described above. Converting natural sources of energy into useful forms and in the quantities needed for industrial, transportation and domestic use is a relatively recent development. The rate of such conversion has been rising as standards of living have improved and the populations have grown. Different sources of energy have been harnessed and many different energy utilization technologies have been invented. Conversion technologies have largely kept pace with demands, and newer utilization modalities often require “higher quality” forms of energy, such as electricity. Some of the traditional sources of energy, such as fossil fuels, are being depleted at faster rates. Technologies required to harness other, less traditional sources, such as renewable energy, have not kept pace with the rising demands of developed and more significantly developing countries. These trends are causes for concern, and more recently, even more troubling trends have emerged. While environmental issues associated with the use of some energy sources have been addressed and largely mitigated, others are only beginning to be understood, and some have yet to be explored carefully. For the latter, carbon dioxide and its role in global warming stand out, and currently pose the most vexing problems.

To appreciate the scale of the challenge, we start with reviewing the current energy consumption rates, and the raw/crude sources of this energy. This is summarized in Section 2. The U.S. is the World’s largest consumer of energy, and it helps to contrast the sources/forms of raw energy used in the U.S. with those used worldwide. In order to do that, we look at the relation between the per capita energy consumption and the gross national product, and how this correlation has changed over time for a number of countries. The disparity of consumption is staggering, and while the per capita consumption of developed countries is stabilizing, it is still multiples of that of developing nations. Energy consumption in parts of the developing world is growing fast, especially in the some of the most populated countries. Another important factor in projecting forward is the pattern of energy utilization, that is, how much energy is used in different sectors of the economy, and how different forms of raw energy are used. Finally, the expected growth in energy consumption, and the changing pattern by source, is quoted from the recent International Energy Agencies predictions. Given that currently more than 85% of our energy is supplied from fossil resources, it is also important to consider how much might be left, and the time scales of exhausting these resources.

Energy consumption rates, now and in the near future, highlight some of the challenges of meeting the needs of a growing population that is striving to improve its standards of living especially when considering the limitations on fossil fuel resources and reserves. On the other hand, global climate change, believed to correlate to the accumulation of greenhouse gases in the atmosphere, poses an even more urgent and demanding set of questions. These are related to predicting reliably the impact of carbon dioxide ($CO_2$) on the global temperature and anticipating the impact of global warming on life and the health of the planet. Evidence of global warming over the past century, and its correlation to $CO_2$ concentration in the atmosphere is rather compelling, but predicting precise future trends using current knowledge and tools is a subject of current debate. This is not surprising given the complexity of climate modeling and the uncertainty associated with projecting energy sources and consumption scenarios and other factors that will determine the changes in weather pattern, sea level, ocean acidity, etc. There is, however, a general agreement that the historic trend of gradual rise of global temperature starting with the onset of the Industrial Revolution will continue. This is reviewed in Section 3. Attempts to understand how these changes in the global temperature can affect human life are beginning to emerge, and some scenarios for addressing these concerns are highlighted.[1]

Technology has led to the enormous expansion of energy resources and utilization, and the vast and concomitant improvement of the quality of life. Technology is also expected to suggest solutions that address resources depletion and $CO_2$/climate change predicament. This is discussed in Section 4. Achieving higher efficiencies, expanding the utilization of low carbon energy sources, and implementing carbon dioxide capture and sequestration are the three primary approaches to lowering $CO_2$ emissions without negatively impacting progress. A one-solution-fits-all scenario cannot work given the wide range of utilization patterns, the geographic distribution of raw energy resources, and the need to adapt the approaches to local conditions. Making smart choices requires balancing the monetary cost; the environmental impact; the time scale for the introduction of new technologies, and their potential for implementation at scale. Several strategies have been proposed most of them depend on the implementation of a portfolio of solutions that contribute to the overall goal of reducing and eventually capping $CO_2$ emissions. The list of possible solutions is far from exhaustive, and is merely suggestive of what can be done. Many factors should also be considered, besides the technology readiness, and some of these are discussed in this paper.

Efficiency improvements must be at the forefront of the effort to conserve resources and reduce the impact of energy consumption on the environment. This applies equally to the efficiency of converting raw energy sources to useful forms in, e.g., that of power plant, vehicle powertrain, light bulbs, etc., and to better practices in utilizing the final products, e.g., better insulation to reduce heating and air conditioning loads, building lighter vehicles, utilizing passive solar, etc. There is a need to define a common basis for comparing different options of using available raw sources to fulfill certain needs. For this purpose, one often needs to evaluate the overall life-cycle efficiency, or the well-to-wheel efficiency, the associated emissions and other environmental implications. In such analysis, energy consumed in the extraction of the raw source, production and transmission of the energy carrier, storage of that carrier,[2] and the production of the equipment used in all these processes must be considered before one can decide on the route with the highest overall efficiency. Defining the energy input to these processes, or the system boundary, is critical to drawing meaningful comparisons between different options.

Given the current infrastructure and end-product utilization patterns, it is unlikely that the dependence on fossil fuels as the major raw source for electricity generation, transportation fuel production, and industrial use will change significantly in the coming decades. Thus, unless carbon dioxide can be captured at scale and stored underground safely, the current alarming trends in global temperature may continue unchecked. Section 5 describes recent progress in developing approaches to “decarbonizes” power generation plants burning heavy hydrocarbons. Approaches that use combustion augmented with separation technologies to remove $CO_2$ from the exhaust gases, to precombustion capture technologies such as gasification, partial oxidation and membrane separation, or those employing oxy-combustion with hypercritical $CO_2$ cycles have been suggested. More efficient electrochemical conversion and separation has also been suggested and promise to further reduce the $CO_2$ capture penalty, when the necessary hardware becomes available. Many of these $CO_2$ capture processes can be extended to the production of low carbon fuels, including hydrogen, from heavy hydrocarbon sources. In this case, most of the carbon in the original fuel is removed in the form of $CO_2$ and transported to safe storage locations.

Zero-carbon energy sources include nuclear energy and renewable sources, such as hydraulic power, geothermal, wind and solar energy and some forms of biomass. Nuclear energy, despite slow expansion for many years, provides 20% of the US electricity and more than 85% of electricity in France. Concerns about security and safety, waste disposal and proliferation of nuclear weapons have limited the expansion of this scalable energy source. Progress has been made in addressing several of these issues, which may lead to the resurgence of nuclear energy. Hydraulic power is considered by many to be close to saturation. Other low-density renewable sources, currently dominated by biomass especially in rural communities, their potentials and recent progress in their respective technologies are described briefly in Section 6. While promising, challenges remain in expanding the utilization of renewable sources, including scalability, cost, footprint and overall complexity associated with their intermittency and the need for storage. Many options are being considered, and growth in wind and solar has been impressive during the past decade. The potential for the long-term use of renewable sources in transportation is particularly interesting. In this case, selecting among many alternatives requires carefully weighing the cost of the new infrastructure, and the efficiency of using a dispersed resource, storage, etc. Many intermediate options must be considered.

Transportation consumes a significant fraction of the total energy worldwide (and close to 27% in the U.S.) and contributes a proportional fraction of $CO_2$ emissions. This is because transportation is nearly solely dependent on fossil fuels,[3] primarily oil. Coal, natural gas, nuclear and renewable energy contribute to electricity generation, besides some oil. While carbon capture and sequestration from stationary power plants using fossil fuels can be used to reduce their “carbon footprint”, this option is not available for transportation vehicle unless hydrogen generated from fossil fuels reforming with capture and sequestration is used. While the use of hydrogen in internal combustion engines and low-temperature fuel cells has been considered, hydrogen for transportation offer other challenging such as charging and onboard storage. Recent trends in transportation technologies are reviewed in Section 7, and relative well-to-wheel efficiencies of different options are discussed.

After traveling the journey of energy conversion from its raw forms to some useful forms to the point where it ultimately dissipates into low-temperature heat, and after reviewing the growing impact of energy consumption on our environment especially with regard to $CO_2$, we conclude by emphasizing the need to pursue the prudent approach of conserving the available resources, harnessing a more diverse portfolio of resources and controlling the emission of greenhouse gases.[4] While technology offers the requisite set of solutions to achieve these objectives, economics, policy and public awareness are necessary for the timely and successful implementation of the technical solutions.

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[1] See Ghoniem AF. Energy and climate change and how to avoid a man-made disaster, Chapter 8 in large-scale disasters: predictions, control and mitigation, Ed by M. Gad-el-Hak, Cambridge University Press, 2008, pp. 177–211.

[2] In this sense many forms of “energy” we use are “energy carriers”, including many forms of refined fuels and electricity.

[3] According to the Department of Energy, Energy Information Administration (2007), the breakdown of transportation fuel in the U.S. is as follows: petroleum 96.3%, natural gas 2.1%, biomass 1.2%, and electricity 0.3%. http://www.eia.doe.gov/oiaf/1605/gg04rpt/carbon.html.

[4] Raw sources are often quasi-stable chemical, nuclear, thermal, potential, or other “high-grade energy sources,” although low-grade sources are also used.

## 2. Energy consumption, now and then

### 2.1. How much we use now

The world consumes more than 440 EJ annually, and the consumption rate is rising steadily, with a positive second derivative starting at the onset of the 21st century. According to the International Energy Agency (IEA), the world power capacity in 2003 was close to 14 TW; 3.3 TW were in the US [1]. Of the current total consumption:

- Close to 82% is produced from fossil fuels (petroleum, natural gas and oil, with a very small fraction of nonconventional sources such as tar sands);
- 10% comes from biomass formed primarily from combined agricultural and animal products, and mostly converted to thermal energy through combustion; and,
- Nuclear fission, hydroelectric and other renewable energy such as geothermal, wind and solar, supplying the rest of the current energy mix.

According to the same report, the total world capacity is expected to reach beyond 50 TW by the end of the 21st century, driven by population growth and the rise in living standards especially in developing countries. This will occur despite the anticipated improvement in energy intensity, defined as the gross domestic product per unit energy used, or GDP/J, and the reduction in the carbon intensity of the fuel mix, defined as the energy produced per unit mass of carbon used, J/C. The growth rate of energy consumption in developed countries is likely to slow down as their population growth stabilizes and their energy efficiency continues to improve. This slow down will be balanced by significant growth rates of energy consumption in the developing world. It is interesting to note that the massive expansion in energy consumption started with the Industrial Revolution, nearly 150 years ago. Since then, technology has been applied to discover and harness more raw sources of energy, but also to invent more direct and indirect uses of energy, such as transportation, lighting, air conditioning, computing, etc.

Fig. 1 shows the breakdown of the World *primary* energy consumption in 2004, as compiled by the International Energy Agency (IEA). The total is 11,059 Mtoe/y (million tonne oil equivalent), which is equivalent to 462 EJ/year for that year.[5] Fossil fuel use, measured by the total thermal energy equivalent, is currently dominated by oil, followed by coal and natural gas, but the last is catching up fast. Oil is the fuel used mostly in the transportation sector. Coal is used mostly in electricity generation, where the consumption of natural gas has also been rising. Of the total energy consumption worldwide, the IEA estimates that oil contributed 34.3%, followed by natural gas and coal, at 20.9% and 25.1%, respectively. The IEA uses a conversion factor for each form of fossil fuel, and for electricity, to estimate the oil equivalent of the energy. For instance oil, on average, has 1 toe/tonne, while coal has almost 0.5 toe/tonne[6] (in conventional energy units, 1 Mtoe = 41,868 TJ). The first law efficiency for geothermal energy is 10%. The contributions of nuclear and renewable sources such as hydropower, which produce electricity, are converted to thermal energy using First Law efficiencies as shown next. Most of the renewable electricity is generated from hydroelectric power, contributing 2.2% of the total energy. The IEA uses 100% efficiency to represent the energy content of electricity. Nuclear energy contributes 6.5% of the total primary energy. The IEA uses 33% efficiency to convert nuclear electricity to thermal energy. Biomass, geothermal, solar and wind generate the rest. Thus, currently and worldwide, almost the same amount of electricity is generated from nuclear and hydraulic sources.[7] Biomass sources contribute the large majority of this part of the renewable[8] energy, used mostly in rural communities where it constitutes a significant source of energy for heating and cooking. As shown in Fig. 1, the total contributions of nonhydraulic, non-biomass renewable sources are 0.4%. Wind and solar utilization, however, have been growing rapidly. Biomass conversion to liquid fuels is also gaining some momentum in developed countries.

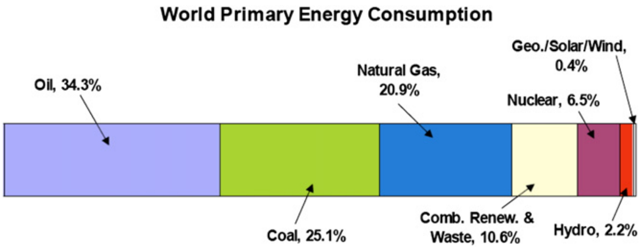

**Fig. 1.** The breakdown of the World primary energy consumption in 2004. The total is 11,059 Mtoe (million tonne oil equivalent). Except for hydropower, the primary energy measures the thermal energy equivalent in the fuel that was used to produce a useful form of energy using Mtoe. For nuclear energy, an average efficiency of 33% is assumed for converting the electrical energy to thermal energy, while for geothermal energy the efficiency is 10%. When energy is obtained directly in the form of electricity, such as hydropower, wind and photovoltaic, the energy equivalent of electricity is used. Source: data downloaded from IEA Key World Energy Statistics, 2006 Edition, page 6, 1973 and 2004 Fuel Shares of Total Primary Energy Supply. PDF document downloadable from: http://www.iea.org/Textbase/publications/free_new_Desc.asp?PUBS_ID=1199. Website visited on 7/12/07. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

### 2.2. Energy and how we live

Energy is strongly correlated with the quality of life as measured by industrial productivity; abundance of agricultural harvest and clean water; convenience in transportation; and human comfort and health. Our welfare depends on continuous and guaranteed supplies of different forms of energy, on demand and at different scales, at affordable rates and all the time. It has been shown the per capita gross domestic product correlates well with the per capita energy consumption, with developed countries consuming energy at orders of magnitude higher than those of developing and poorer nations (see Fig. 2 [2]). Even among developed nations, some countries consume at multiple the rates of others (compare the per capita energy consumption of the US and that of Japan). And while the overall energy efficiency of developed countries has constantly improved as the productivity of their economies grew, there is still a significant gap between energy consumption in developed and developing countries. As will be shown next, one can define an affluence index based on the per capita energy consumption.

On average, energy consumption worldwide has grown nearly by 1.55%/year for the period from the mid Eighties to the mid Nineties, with the US consumption growing at 1.7%, China at 5.3% and India at 6.6%. The economies of China and India have grown at

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[5] EJ is an exajoule, or $10^{18}$ J, and 1 TWh = 0.086 Mtoe.

[6] Note that a megaton = 10**6 ton = 10**9 kg.

[7] It should be noted that older statistics used to consider the same conversion efficiency for nuclear and hydraulic electricity, and used to show a similar percentage for both sources when compared to fossil sources. It is also noted that reporting energy statistics does not follow uniform standards and care must be taken in differentiating “primary” energy and electricity.

[8] Renewable sources have also been called nonexhaustable sources, which is a more technically sound but less frequently used label.

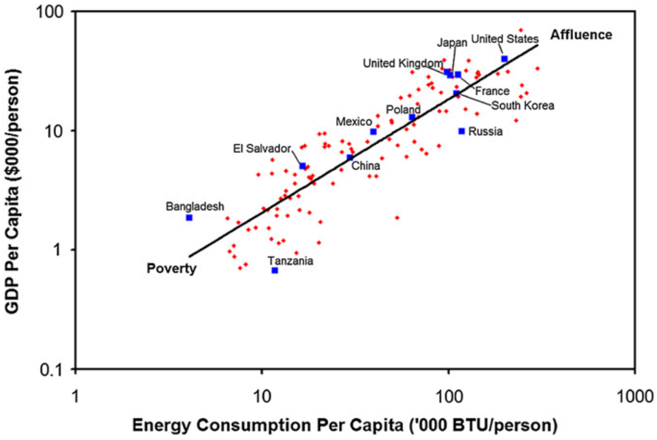

**Fig. 2.** The per capita energy consumption and the per capita GDP for a number of developed and developing countries (note that 1 BTU = 1.055 kJ). Energy use per capita is for the year 2003, GDP per capita is given for the year 2004 expressed in 2000 dollars. Source: data downloaded from the United Nations Development Programme, Human Development Report (HDR) 2006, Table 1, pages 283–286, and Table 21, pages 353–356. http://hdr.undo.org/hdr2006/report.cfm. Website visited on 7/12/07. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

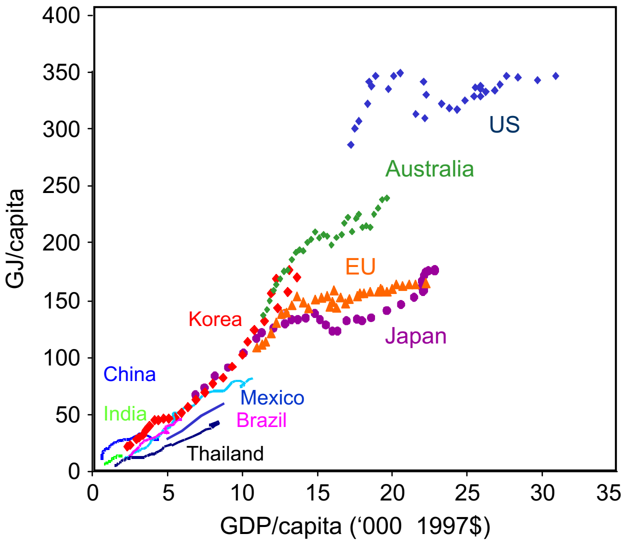

**Fig. 3.** Dependence of the per capita energy consumption on the per capita GDP, plotted over a number of years. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

comparable rates, demonstrating the correlation between the growth in energy consumption and the conditions of the economy.

Increasing the per capita gross domestic product (GDP) of a country goes hand-in-hand with the rise in its per capita energy consumption, especially during the early stages of development. This trend slows down as the economy matures and becomes more energy efficient, as in the case of the US, the EU and Japan. Fig. 3 shows the rise of the per capita energy consumption against the GDP/capita for a number of developed countries and some developing countries, as well as those undergoing a fast transition. Many developed countries show significant improvement in energy efficiency as the per capita GJ stabilizes while the GDP continues to rise significantly. This trend is enabled by investing in energy efficiency, both conversion and utilization efficiencies; adopting advances in technology that lead to energy saving; and to citizens becoming more aware of the environmental impact of wasteful energy utilization. Rising energy prices often promote trends towards lower consumption, enabled primarily by switching to higher efficiency systems, but the impact often persists even after energy prices fall back to more affordable levels. Transitional economies are still in the fast consumption rise phase and have not shown moderating trends yet. Some developing countries have started to take significant steps towards improving their economic conditions through industrialization, agricultural mechanization and large-scale infrastructure improvement, causing their energy consumption to grow at a faster rate in the last few years. In particular, China and India, two of the largest countries in the World, have experienced fast rise in economic activities lately and a concomitant increase in energy production and consumption. Neither country is expected to reach a steady state in its per capita energy consumption soon because of the large population fraction that is yet to participate in the economic improvement. Changes in these economies are expected to drive most of the growth in the overall worldwide energy consumption and $CO_2$ emissions.

Consumption patterns vary widely and depend on the economy, local weather and population density, among other factors. The US energy consumption, which amounts to 25% of the worldwide total (with less than 5% of the population), was more than 100 EJ in 2007. The US energy consumption is almost twice that of China and four times that of India. Both countries are planning to double their energy consumption over the next 15–20 years. Of the total consumption in the US, 28.64% went into transportation; 31.18% went into industrial production; 18.14% went to commercial buildings; and 21.4% to residential buildings [3]. Source-wise, 84.89% of the total energy in the US was generated from fossil fuels, 8.26% from nuclear and the rest from renewable sources including biomass, hydroelectric and GWS (geothermal, wind and solar, in that order). The share of different sources and the utilization in different sectors is shown Fig. 4, with a total of 101.6 QBTU.[9] Of that, almost 39.82 QBTU comes from petroleum, 22.77 QBTU comes from coal, and 23.64 QBTU comes from natural gas, 8.41 QBTU from nuclear electricity, 3.62 QBTU comes from biomass, 2.459 QBTU from hydroelectric power, and 0.752 QBTU from geothermal, wind and solar energy (0.342 QBTU in geothermal, 0.342 QBTU in wind, and 0.068 QBTU in solar).[10] Currently, consumption is projected to rise over the next 25 years, with the fossil fuel share reaching 89%. At the other extreme, we note that nearly 25% of the world population does not have access to electricity and nearly 40% rely on biomass as their primary source of energy.

It should be noted that in their effort to raise their standards of living and quality of life, it is not necessary for developing nations to match the energy consumption models and measures of developed countries. Attempting to match the average energy consumption rates of developed countries would nearly be an impossible goal given the available resources and the associated monetary and environmental costs. Higher quality of life in developing countries could be achieved at energy intensity lower than the current standard in developed nations. For instance, it has been shown that the UN human development index (HDI), which includes data that reflect the physical, social and economic health and well being of a population such as the per capita GDP, education, longevity, use of technology, and gender development, rises steeply during the early stages of growth in the per capita electricity consumption before it levels off at much higher electricity consumption rates [2]. That is, a “point saturation” of energy consumption is reached beyond

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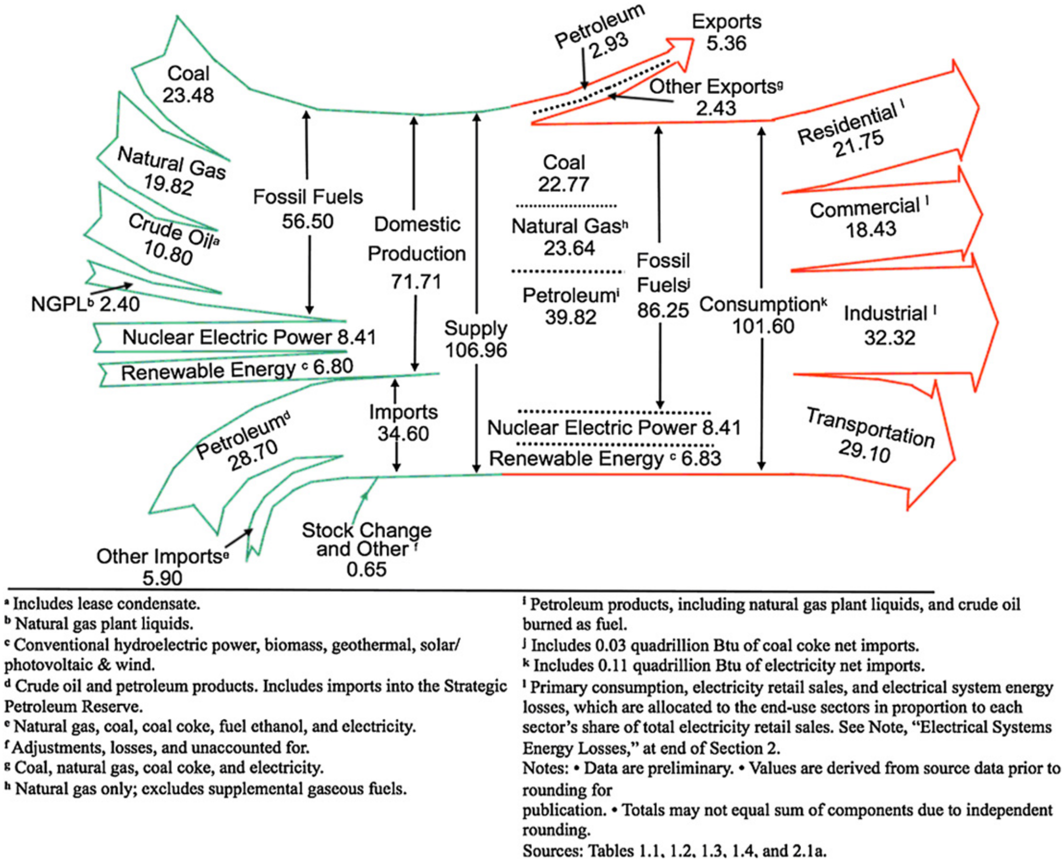
[9] Quadrillion BTU (QBTU) = 1.055 EJ = 1.055 10**18 J.

[10] http://www.eia.doe.gov/cneaf/alternate/page/renew_energy_consump/rea_prereport.html.



[a] Includes lease condensate.
[b] Natural gas plant liquids.
[c] Conventional hydroelectric power, biomass, geothermal, solar/photovoltaic & wind.
[d] Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.
[e] Natural gas, coal, coal coke, fuel ethanol, and electricity.
[f] Adjustments, losses, and unaccounted for.
[g] Coal, natural gas, coal coke, and electricity.
[h] Natural gas only; excludes supplemental gaseous fuels.
[i] Petroleum products, including natural gas plant liquids, and crude oil burned as fuel.
[j] Includes 0.03 quadrillion Btu of coal coke net imports.
[k] Includes 0.11 quadrillion Btu of electricity net imports.
[l] Primary consumption, electricity retail sales, and electrical system energy losses, which are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note, "Electrical Systems Energy Losses," at end of Section 2.

Notes: • Data are preliminary. • Values are derived from source data prior to rounding for
publication. • Totals may not equal sum of components due to independent rounding.

Sources: Tables 1.1, 1.2, 1.3, 1.4, and 2.1a.

**Fig. 4.** Energy sources and consumption patterns in the US, 2007 data, measured in quadrillion BTU, where QuadBTU or QBTU = 1.055 EJ (Adopted from the Energy Information Administration/Annual Energy Review 2007 [3] http://www.eia.doe.gov/aer/pdf/pages/sec1_3.pdf). The units used here represent the thermal energy content of the fuel. In case of nuclear and renewable energy, which is dominated by hydropower, where the energy output is electricity, an assumed First Law efficiency is used to convert the electricity to thermal energy. The efficiency used in assembling these data is an average over fossil fuel power plants. Please note that some of the conversion factors used in the IEA and the EIA are different. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

which more energy use does not necessarily translate to better standard of living. Similar trends can be observed in Fig. 3 where the per capita GDP continues to rise at a near constant energy consumption per capita, after the latter reaches a certain threshold.

### 2.3. How much we will use

According to the International Energy Agency [1], the total worldwide energy consumption is expected to rise by more than 50% over the next 25 years, while the fractional share of the different raw sources in the total amount is not expected to change significantly. The share of fossil fuels is predicted to grow slightly, as shown in Fig. 5 [3]. Meanwhile, the relative share of natural gas is expected to exceed that of coal because of the growing use of natural gas in electricity generation, while liquid petroleum will continue to be the largest source of energy because it is the primary source for transportation fuels. Given the large matrix of parameters affecting energy supply and demand, the economic conditions and population growth, predicting the growth in energy consumption and the availability of energy sources is risky and is prone to errors and uncertainty. However, historical trends show that changes in consumption pattern occur rather slowly, given the large infrastructure that support resource extraction, conversion and supply of energy, as well as the current patterns of energy utilization. Change requires massive investment and a population willing to support such investment. Change often follows the discovery of newer sources of energy, for instance the rise in petroleum consumption and the fall of coal utilization in mid century following the discovery of vast petroleum reserves. Change can also result from the wide availability of technologies that enable the large-scale introduction of alternative sources, e.g.,

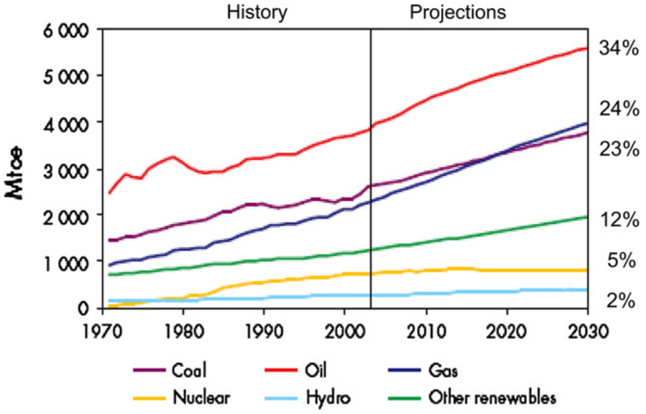


**Fig. 5.** World energy consumption energy since 1970, and projections towards 2030. Source: the International Energy Agency, World Energy Outlook 2005, page 5, Fig. 2.1, World Primary Energy Demand by Fuel in the Reference Scenario, http://www.Worldenergyoutlook.org/free.asp. Website visited on 7/12/07. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

nuclear energy or cheap photovoltaics. Economic factors largely dictate the large-scale utilization of a particular energy source.

Other sources of liquid fuels, such as tar sands or oil shale, may contribute a fraction of the transportation fuel need in the future, hence displacing some of the oil consumed in this sector. The production of liquid fuels from these heavy hydrocarbon sources becomes more economical as oil prices rise and the concern over the security of oil supplies intensify. Plentiful and widely distributed coal resources can be used to produce liquid transportation fuels, as will be shown later. It is likely that the production of electricity using wind and solar technologies will continue to grow as the prices of this "renewable electricity forms" drop to values closer to that produced by burning coal and natural gas. Biomass sources contribute to energy production in the form of heat and electricity. Biomass-based ethanol contributes to transportation fuels, both as primary fuel or fuel additive, although at a very small scale. Harnessing biomass energy, a relatively low $CO_2$ energy source, is partly motivated by the concern over global climate change as well as energy security (life-cycle $CO_2$ emission resulting from biomass is complex and will discussed later in the paper). It is predicted that the growth of energy consumption, given the current fuel mix, will result in 50% rise in $CO_2$ emissions during the same 25-year period. Given the challenges in scaling up renewable resources to meet the growing demand, it is not unlikely that nuclear energy growth will exceed current projections especially if the problems with waste storage and security are resolved satisfactorily. Challenges to future expansion of nuclear energy are discussed in later sections.

Fossil fuels reserves are defined as those known to exist, i.e., have been discovered and can be extracted economically using existing technologies. On the other hand, fossil fuel resources are defined as those thought to exist but their extraction may require advanced technologies and may not be presently economical. It has been argued that the combined reserve and resource base of fossil fuels have a finite lifetime, perhaps 100–300 years, depending on the fuel type, recovery rate, search and production technologies, exploration and consumption rates.[11] Current predictions indicate that the lifetime of oil ranges from 50 to 75 years for the reserve, while resources are predicted to last for 150 years. Natural gas is expected to last nearly twice as long as oil. Coal, on the other hand, is plentiful and is expected by some to last for several hundreds of years. These estimates are approximate at best, since the recoverable amount of the reserve is strongly dependent on the available recovery technology, cost and consumption pattern. With the current projections of reserves and resources, it is coal that will last the longest, with oil running out the fastest. Coal is available worldwide and in many of the fast-developing economies, like China and India. Taking into account other heavy sources of hydrocarbon, such as oil shale and tar sands, recoverable liquid fuels estimate increase substantially. For instance it is estimated that while the proven reserves of oil are nearly 1 trillion barrels, Canadian oil sands could produce 1.7 trillion barrels, and oil shale in the U.S. could produce 2 trillion barrels. Of course, this does not say much about the price of such products, and how depleting the existing resources might impact the affordability, especially those of oil and gas, and hence impact the consumption rate. The environmental impact of producing light hydrocarbons from tar sands and oil shale could also be significant. Other hydrocarbon resources include deep ocean methane hydrates, which are thought to be a viable vast source if the technology is developed for bringing them up without disturbing their original state or the health of the oceans. A case for the existence of abiogenic (nonorganic) methane in deep underground formation has been made, and if proven, would be another vast resource [4].

The growing evidence of the correlation between the global temperature and the carbon dioxide concentration in the atmosphere has prompted calls for increasing the use of low carbon or zero-carbon energy sources, or preventing $CO_2$ produced in fossil fuel combustion from entering the atmosphere. Since the beginning of large-scale industrialization and the fast rise in hydrocarbon consumption, atmospheric concentration of $CO_2$ has grown from 280 ppm to 360 ppm. Electric power generation has been and will remain the major source of these gases, followed by transportation, with industrial and residential contributions following at smaller rates. The reason for this is that electricity generation plants use coal extensively, although the use of natural gas has been rising (nuclear and hydraulic sources make up a smaller share of electricity production). Since they are stationary, electricity generation plants should be considered as an easier target for reducing carbon dioxide emission per unit useful energy produced, through efficiency improvement or $CO_2$ capture and storage, as will be explained later.

## 3. Carbon dioxide

The prospect of the rise in fossil fuel consumption, especially those with high carbon content such as coal, oil and other heavy hydrocarbons has led some to warn against irreversible global warming and the associated impacts of climate change. The same trends have prompted others to call for national and international intensive efforts to develop technologies that can generate the extra energy needed by mid century, that is up to 10 TW, using carbon-free sources [5]. These concerns arose from demonstrated evidence that the rise of atmospheric concentration of carbon dioxide and the global average temperature are correlated, and that the rate of increase of carbon dioxide concentration in the atmosphere may accelerate if the projected growth in carbon-based fuels is materialized [6]. This correlation is shown in Fig. 6. One of the striking features of this correlation is the simultaneous rise of $CO_2$ and the temperature starting around the time of the onset of the Industrial Revolution, when consumption of fossil fuel experienced sudden acceleration that has continued until today.[12]

### 3.1. Greenhouse gases

Global warming, that is, the rise in the Earth surface and near surface temperature by slightly more than 1 °C over the past 150 years is thought to be connected to the rise in the concentration of greenhouse gases in the atmosphere during the same period. Greenhouse gases are defined as water ($H_2O$), $CO_2$, methane ($CH_4$), nitrous oxide ($N_2O$), chlorofluorocarbons (CFCs) and aerosols. The greenhouse potential of $CO_2$, $CH_4$, $N_2O$ and CFC (taken as averages among different estimates) is 1:11:270:1300–7000 (with the latter

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[11] For more on the subject, see "Out of Gas: The End of the Age of Oil" by D Goodstein, (2004) Norton and Co., New York, NY, "Hubbert's Peak: the Impending World Oil Shortage" by K.S. Deffeyes (2001), Princeton University Press, Princeton NY, and ASPO website http://www.peakoil.net.

[12] For more data on the global mean temperature, the surface temperature anomaly (difference from historical means), and impact of solar irradiance variation of global mean temperature, see http://data.giss.nasa.gov/gistemp/2007/. On a yearly average basis, the solar insolation (total energy received by an area perpendicular to a beam) at the outer edge of the Earth atmosphere is 1366 W/m$^2$. It has been observed recently that despite the small decrease in the solar irradiance, the global temperature continued to rise, providing further evidence to the greenhouse gas mechanism.

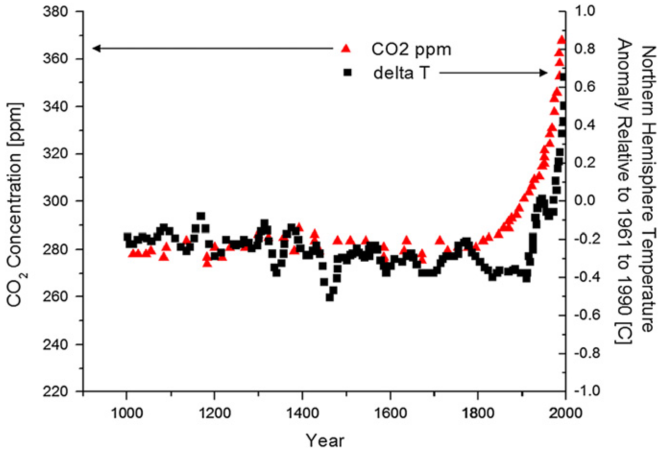

**Fig. 6.** The rise in atmospheric concentration of $CO_2$ and global average temperature over the past 1000 years. Source: data taken from the IPCC Third Assessment Report 2001, Working Group I, Technical Summary. Figure is combination of data from Fig. 5, page 29, Millennial Northern Hemisphere (NH) Temperature Reconstruction, and Fig. 10b, page 40, CO2 concentration in Antarctic ice cores for the past millennium. Recent atmospheric measurements (Mauna Loa) are shown for comparison. Html version available online at: http://www.grida.no/climate/ipcc_tar/wg1/010.htm. Website visited on 7/12/07. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

depending on the particular type of CFC).[13] Most carbon dioxide anthropogenic emissions result from fossil fuel combustion, with a small fraction from cement production. It is predicted that continued emissions of greenhouse gases at the anticipated rates would lead to a rise of 2X–3X in their concentration in the atmosphere by the end of the twenty first century, in proportion to the rise in energy consumption. It is interesting to note that Arrhenius [7] predicted an increase of the Earth surface temperature by 5–6 °C due to the doubling of $CO_2$ concentration in the atmosphere, more than a hundred years ago. Fig. 6 shows the rise of the global temperature over the past 150 years, following a long plateau since the year 1000, although a slowing trend was observed in the 1950ties.

### 3.2. *Global energy balance*

The energy fluxes to and from the Earth atmosphere, and their change as radiation passes through the atmosphere are shown in Fig. 7. Solar radiation is concentrated at short wavelengths, within the visible range of 0.4–0.7 micron, because of the high temperature of the surface of the sun, estimated approximately to be 6000 C. Only a small fraction of solar radiation lies in the ultraviolet range, down to 0.1 micron, and in the infrared range, up to 3 micron. On average, 30% of the incoming solar radiation is reflected back by the Earth's atmosphere and its surface (the albedo), 20% is scattered by the Earth atmosphere at different altitudes, and the remaining 50% reaches the surface and is absorbed by the ground and the water. The fraction of the incoming radiation that is either absorbed or scattered while penetrating the Earth atmosphere does so in a spectrally selective way, with the ultraviolet radiation absorbed by stratospheric ozone and oxygen, and infrared radiation absorbed by water, carbon dioxide, ozone ($O_3$), nitrous oxide and methane in the troposphere (lower atmosphere). Much of the radiation that reaches the ground goes into evaporating water from the oceans. Outgoing radiation from the cooler Earth surface is concentrated at the longer wavelengths, in the range of 4–100 micron.

Greenhouse gases in the atmosphere absorb part of the outgoing radiation, with water molecules absorbing in the 4–7 microns wavelength as well as at 15 microns, and carbon dioxide absorbing in the range of 13–19 micron. A fraction of this energy is radiated back to the Earth surface and the remaining is radiated to outer space. The change of the energy balance due to this greenhouse gas radiation is known as the radiation forcing of these gases, and its contribution to the Earth energy balance depends on the concentration of the greenhouse gases in the atmosphere. The net effect of absorption, radiation and re-absorption is to keep the Earth surface warm, at average temperature close to 15 C. In essence, the Earth atmosphere acts as a blanket, without it the surface temperature could fall to values as low as −19 C. Because of its concentration, carbon dioxide has the strongest radiation forcing among known greenhouse gases, except for that of water. However water concentration in the atmosphere is least controlled by human activities.

Increasing the concentration of greenhouse gases enhances the radiation-forcing effect. Moreover, a number of feedback mechanisms, such as the melting of the polar ice (which reflects more of the incident radiation back to space) and the increase of water vapor in the atmosphere (due to the enhanced evaporation resulting from higher temperatures) are expected to accelerate the greenhouse contribution to the rise of the mean atmospheric temperature.

Current estimates indicate that fossil fuel combustion produces almost 6 GtC/y. This unit, gigaton carbon per year, is used to account for all forms of carbon injected into the atmosphere, with carbon accounting for 12/44 of carbon dioxide, that is 1 GtC is equivalent to 44/12 = 3.667 $GtCO_2$. This amount of fossil fuel combustion produced carbon should be compared with other sources/sinks that contribute to carbon dioxide concentration in the atmosphere. Carbon dioxide is injected into the atmosphere through respiration and the decomposition of waste and dead biomatter, and is removed by absorption during photosynthesis and by the phytoplankton living in the oceans. Respiration produces nearly 60 GtC/y, while photosynthesis removes nearly 61.7 GtC/y, with a balance of a sink of 1.7 GtC/y. The surfaces of the Oceans act as a sink, contributing a net uptake of 2.2 GtC/y, a source/sink balance between production of 90 and consumption of 92.2 GtC/y. Changing land use (deforestation) and ecosystem exchange adds/removes 1.4/1.7 GtC/y, for a net balance of a sink of 0.3 GtC/y. The overall net gain of $CO_2$ in the atmosphere is estimated to be around 3.5 GtC/y. It is relative to these contributions that fossil fuel combustion (and a small amount from cement production) appears significant. However, it must be stated that these numbers are somewhat uncertain and that there is 1–2 GtC/y unaccounted for in the overall balance, when all the uncertainties are traced. Moreover the total capacity of any of these systems is extremely large, and might change in ways that are not well understood. The uncertainty in the numbers is reflected in the different sources, and is demonstrated here by the different numbers in the text and in Fig. 8. Nevertheless, the clear evidence is that carbon dioxide concentration in the atmosphere has risen, showing its most visible sign since the start of the industrial revolution when fossil fuel consumption started to grow at significant rates.[14]

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[13] The global warming potential of a greenhouse gas is a relative measure for the warming potential of different greenhouse gases, accounting for their lifetime in the atmosphere and relative radiative forcing strengths, all normalized with respect to $CO_2$. A unit mass of the gas is considered.

[14] It is estimated that for each 2.1 GtC introduced in the atmosphere, $CO_2$ concentration rises by 1 ppm, and that the average lifetime of carbon dioxide in the atmosphere is 100–200 years.

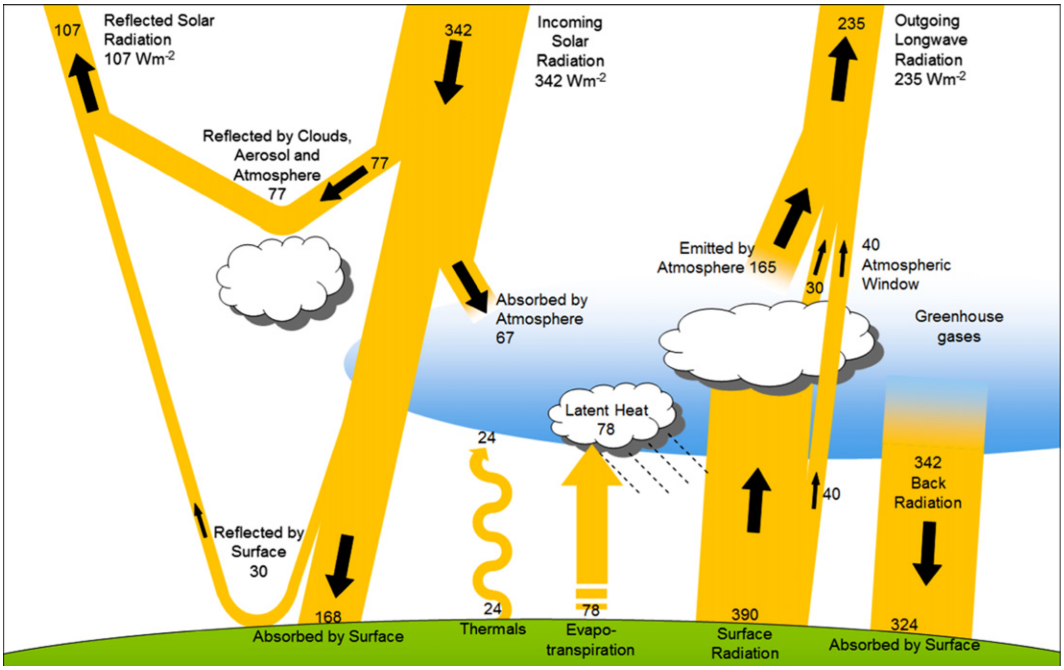

**Fig. 7.** Solar energy flux, how much of it reaches the Earth's surface; the radiation emitted by the ground, and the balance that is re-radiated back to the surface. All numbers are given as averages over the Earth's surface and in units of $\mathrm{Wm}^{-2}$. Adapted from Intergovernmental Panel on Climate Change, Working Group 1: The Physical Basis of Climate Change, Chapter 1, Historical Overview of Climate Change Science, page 96, FAQ 1.1, Fig. 1 (2007). http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Pub_Ch01.pdf, website visited on 7/17/07. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

### 3.3. *Climate modeling*

Global climate models, or global circulation models (GCM) are complex computer models used to estimate the change in the Earth's temperature and carbon dioxide concentration in the atmosphere, among other state variables like pressure, density and wind velocity. These models, when applied to predict the change in global temperature over time, take into account the different scenarios for the introduction of carbon dioxide into the environment, the solar radiation and other parameters that could affect the atmosphere. In essence, these models integrate the time-dependent conservation equations, that is, total mass, momentum, energy and chemical species equations over a global grid that covers the entire surface of the Earth and extends vertically from the ground (including the ocean surface) to some distance in the upper atmosphere (stratosphere) where boundary conditions are imposed (see Fig. 9 [8]). These conservation equations are tightly coupled. The starting point is the Navier–Stokes equations of buoyant flows, the energy equation and a number of transport equations that balance the change of the different chemical species that undergo mixing and reaction in the atmosphere. These equations must be integrated simultaneously since they are coupled through a number of source terms. The energy equation models the response of the atmosphere to the incoming and outgoing radiation across the computational domain, as well as the interior radiation forcing due to the greenhouse gases. It couples the impact of radiation to that generated by mixing, evaporation and condensation, and local reactions. The number of transport equations is determined by the number of chemical components that must be used to define the local chemical state of the atmosphere, including gases and aerosols. The equations describing the GCM may be coupled to those describing ocean circulation models, which are used to predict the change of the water temperature, evaporation rate and evolution of concentration of different gases within that vast body of water. This coupling adds to the accuracy of the overall prediction, but also to the numerical complexity and the computational requirements. Boundary conditions at the ground and on the water surface (or ice surface) must be supplied, depending on the nature of the terrain, the ground cover and the season. Input regarding land use change is also necessary.

The solution of these coupled equations predicts the state of the atmosphere at any moment and location, including the wind velocity, pressure, temperature and concentration of relevant gases and aerosols, over many years. Atmospheric flows are turbulent, driven by local instabilities and experience chaotic dynamics. Solving the governing equations over coarse grids, on the order of many kilometers in each coordinate direction, sacrifices resolution for affordability. Unresolved dynamics are replaced with local mixing and transport models, and many details might be lost or simply averaged over to reduce the computational complexity. Constitutive relations, describing the relations between the different fluxes and the local gradients, and some chemical kinetics reaction mechanisms are necessary to close the system of equations. The problem is compounded by uncertainty[15] at many levels, including the emission scenario, the model structure and the

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[15] Using uncertainty analysis is relatively new in predictive science, but it is gaining attention in areas where models contain unknown or uncertain parameters, or when the model structure itself is uncertain, that is when the relative contribution of the different physical and chemical processes to the outcome is not know apriori. Uncertainty analysis is different from sensitivity analysis. In the latter, one examines the response of the model results to small variations of input parameters around their mean values to determine the significance of these parameters and the relative dependence of the output on the input. In uncertainty analysis, probability distributions of input parameters are propagated through the solution to determine the probability distribution of the output, either directly (symbolically by expanding the solution in polynomial chaos) or indirectly using, e.g., Monte Carlo methods.

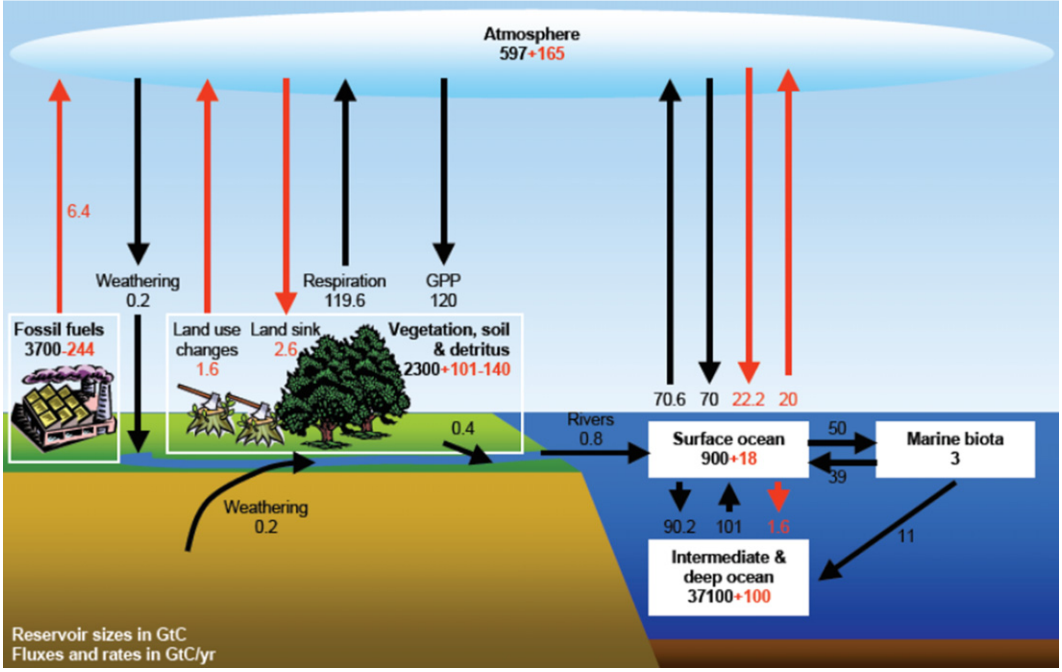

**Fig. 8.** The global carbon cycle for the 1990's, showing the main annual fluxes in GtC/y; pre-industrial "natural" fluxes in black add "anthropogenic" fluxes in red (both the arrows and the associated numbers). Gross fluxes have uncertainty of more than ±20%. GP is gross primary production during photosynthesis. Adapted from Intergovernmental Panel on Climate Change, Working Group 1: The Physical Basis of Climate Change, Chapter 7 Couplings between Changes in the Climate System and Biogeochemistry, page 514, Fig. 7.3 (2007). http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Pub_Ch07.pdf. Website visited on 7/17/07. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

modeling parameters. Since solutions are required for long time, modeling and numerical errors and uncertainty in input parameters may propagate and contaminate the results. Furthermore, the convective nonlinearities of the governing equations, even at the coarse grid level, may lead to critical phenomena that depend sensitively on the initial conditions and the model parameters. Solutions could bifurcate to other regimes if some of the initial conditions change or the parameters deviate from their average values. Many "local" phenomena can also be unstable, and if energized, can trigger large-scale change, such as the disintegration of the large-mass ice sheets. As an example of GCM predictions, the IPCC predictions of the temperature trajectory throughout the 21st century are shown in Fig. 10 for different carbon dioxide emissions scenarios and model construction.

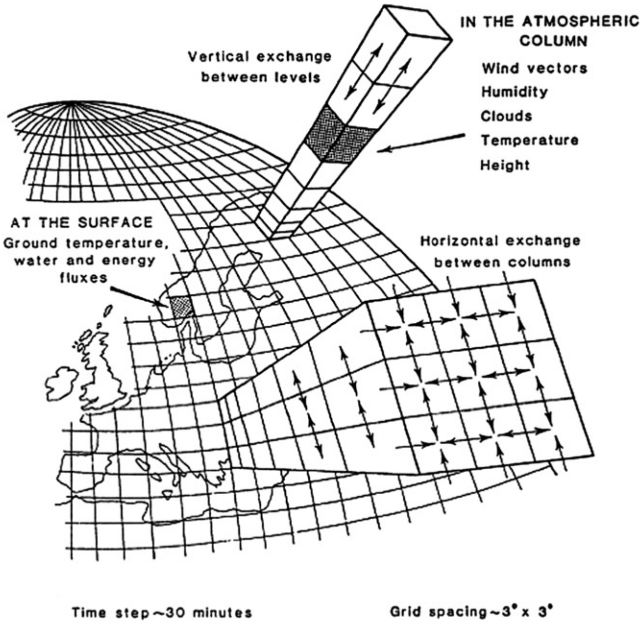

**Fig. 9.** Spatial grid used to define a discrete representation of the governing transport equations (mass, momentum, energy and chemical species) on the Earth's surface and atmosphere, the state variables and the exchange fluxes at each grid volume. This representation is used in global climate (circulation) models. Taken from Tester et al. [8].

Given all these complexities and uncertainties, one would like to study the sensitivities of the solution to many input parameters and to bound the response of the model to the possible range of each input parameters. However, even on a coarse numerical grid, the computational load is enormous and relatively few cases can be predicted at reasonable resolution, even on the fastest available supercomputers. Some further simplifications are often made to reduce the model complexity, such as eliminating dependency on one of the primary dimensions, that is reducing the problem form being three dimensional to being two dimensional, hence by allowing more cases to be run and statistical analysis to be applied to the results. Parametric studies are then used to construct ensemble probabilities for the different outcomes. An example of the results of such modeling is shown in terms of the probability density function of the predicted temperature change with some sources of uncertainties are shown in Fig. 11. As shown there, the predicted rise of 2–3 °C is most probable, and higher and lower values are less, given the limitations of the model and input parameters.

Climate sensitivity, or the incremental change in the global mean climatological temperature resulting from the doubling of atmospheric $CO_2$ concentration, is still being debated, but most models estimate a range of 1.5–4.5 °C [9]. Cloud feedback is the largest source of uncertainty in these model predictions, with

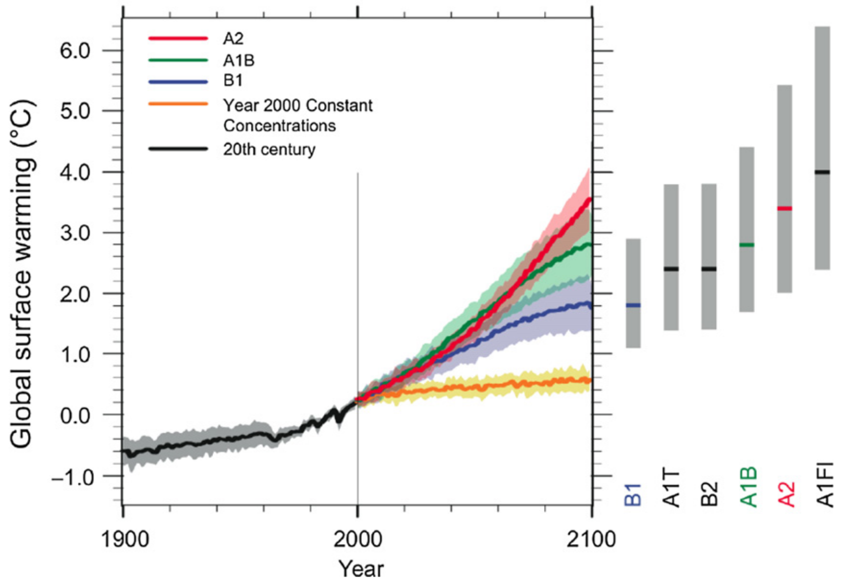

**Fig. 10.** Prediction of the temperature rise during the 21st century, according to different models that account for $CO_2$ emissions and the response of the Earth's atmosphere. Source: IPCC WGI Fourth Assessment Report, Summary for Policymakers, Figure SPM-5, page 14, Multi-model Averages and Assessed Ranges for Surface Warming. Link to PDF is available at http://ipcc-wg1.ucar.edu/wg1/wg1-report.html. Website visited on 7/12/07. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

aerosols, non-carbon dioxide greenhouse gases, internal variability in the climate system and land use change being significant sources of uncertainty.[16] Uncertainty in aerosols radiative forcing remains large. Another source of uncertainty is the rate of heat diffusion into the deep oceans, given the sensitivity of the predictions to how much energy will be absorbed by this massive heat sink. Most predictions focus on carbon dioxide induced climate change, as $CO_2$ is the dominant source of change in the Earth's radiative forcing in all the Intergovernmental Panel on Climate Change (IPCC) scenarios [10].

### 3.4. $CO_2$ emission by fuel and sector

The growing concerns over the correlation between the global temperature and the carbon dioxide concentration in the atmosphere have prompted calls for increasing the use of low carbon or zero-carbon energy sources, or preventing carbon dioxide produced in fossil fuel combustion from entering the atmosphere. Since the beginning of large-scale industrialization, and the fast rise in fossil fuel burning, atmospheric concentration of $CO_2$ has grown from 280 ppm to 360 ppm. Projections for the continuing increase in the amount of carbon dioxide produced in energy production are shown in Fig. 12, both by fuel and the total sum. First, one observes a change of slope at the early part of the 21st century. Given that oil is used to produce more than 40% of the primary energy because of its role in transportation, it is not surprising that it is also the largest source of $CO_2$. In the meantime coal, with a much higher carbon content but lower overall share of the energy contribution, produces nearly the same amount. Natural gas, with the lowest carbon content, contributes the least.

The production of carbon dioxide from different sectors of the economy is shown in Fig. 13 for 2002 and projections until 2030 [11]. The figure shows that electric power generation has been and will remain as the major source of $CO_2$, followed by transportation, with industrial and residential contribution following at smaller rates. Electricity generation plants use coal extensively, although the use of natural gas has been rising, and nuclear and hydraulic sources make up a reasonable share. Since they are stationary, electricity generation plants should be considered as an easier target for reducing $CO_2$ emission per unit useful energy produced, through efficiency improvement or carbon dioxide capture and storage, as will be discussed later. Other stationary sources of carbon dioxide include cement plants, oil refineries, iron and steel industries, etc., where similar opportunities exist. Carbon dioxide reduction from mobile sources is possible primarily through efficiency improvement of existing internal combustion engines or by switching to higher efficiency engines or fuel cells; the use of low carbon fuels such as natural gas, or even zero-carbon fuel such as hydrogen. Electricity-based transportation remains a viable alternative for a low carbon future. In the latter cases, and in a life-cycle assessment (LCA), the source of the zero-carbon energy carrier, that is, hydrogen, or electricity, should be considered as the source of carbon dioxide. This means that total carbon dioxide emission is zero if and only if nuclear energy or "carbon-free" renewable sources is used. Other renewable sources, such as some forms of

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[16] The IS92a scenario of the IPCC assumes that the carbon intensity of the source, that is the carbon to energy (C/E) ratio of the fuel mix, will continue to drop monotonically well into the 21st century, reaching that of NG by 2030 but moving even lower as low or zero-carbon sources, including nuclear and renewable sources, are introduced. In the Second Assessment Report in 1996, the IPCC predicted that the current $CO_2$ concentration of 360 ppm would rise to 750 ppm if the current annual emission of near 24 $GtCO_2$ rises to more than 70 $GtCO_2$ by the end of the century, following the projected rise in energy consumption using the current sources. The corresponding global temperature, according to most climate models would rise by 0.8–3.5 K by 2100. The same calculation shows that the annual carbon dioxide emissions would have to be limited to close to 26 $GtCO_2$ (not far from today's levels) if $CO_2$ is to be stabilized close to 500 ppm by mid century and stay fixed from there on. The carbon dioxide concentration and the temperature rise were revised upwards to 970 ppm and 1.4–5.8 C, respectively, in the Third Assessment Report of 2001. The 90% probability interval in the same results was 1.7–4.9 C. The latter models incorporated revised emission schedules, and more accurate submodels for climate feedback, the radiative forcing of certain gases, and more accurate representation of atmospheric-ocean coupling.

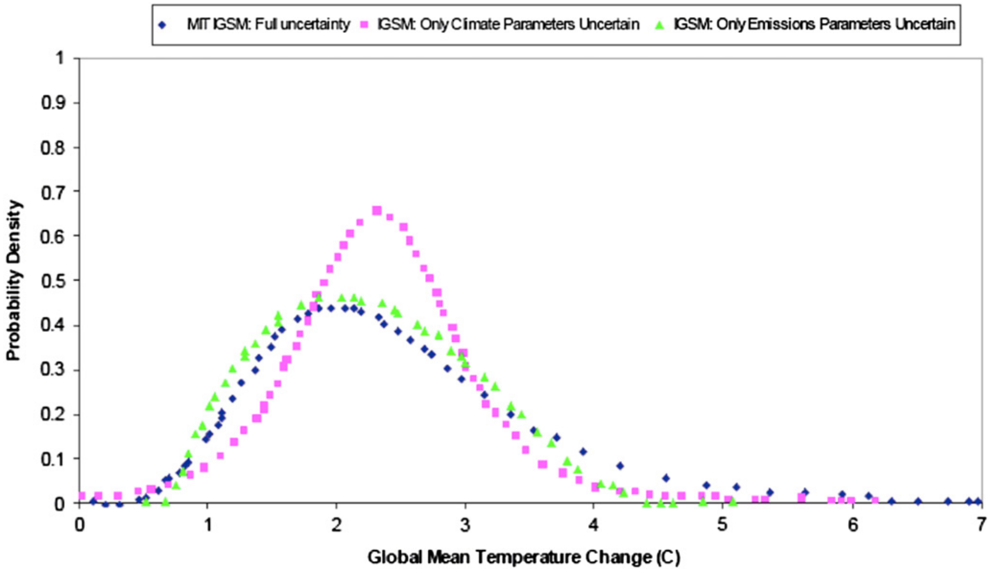

**Fig. 11.** Probability distribution of global mean surface temperature change from 1990 to 2100 with all uncertain parameters (diamonds), only climate model parameters uncertain and emissions fixed (squares) and only emissions uncertain with climate model parameters fixed (triangles). IGSM in the Integrated Global System Model, a model with intermediate complexity for modeling global circulation coupled with an ocean circulation model, and supplemented with necessary emission models. Source: Webster, M., Forest, C., Reilly, J., Babicker, M., Kicklighter, D., Mayer, M., Prinn, R., Sarofim, M., Sokolov, A., Stone, P., Wang, C. Uncertainty Analysis of Climate Change and Policy Response, *Climatic Change* 61: 295–320, 2003. Page 314, Fig. 6, Global mean temperature change, 1990–2100. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

biomass, can be carbon neutral if the source of the biomass feedstock is natural, e.g., grown naturally and harvested manually. Biofuels use fossil fuels in mechanized agriculture and in fuel production, and hence they should not be considered as carbon-free sources.

Estimates of carbon dioxide emissions from burning hydrocarbon fuels to produce useful forms of energy are complex and at times tricky, especially when comparing different pathways or option of how to convert the energy in the original fuel. This is because what we should be interested in is the amount of $CO_2$ emitted per unit useful energy produced from the moment a source is extracted until the final form of the energy is utilized. For instance, an electric vehicle that charges its batteries using electricity from the grid is not a zero emission vehicle since grid power generation is currently mostly fossil fuel based. Moreover, and in a more careful analysis, the emissions in the production and disposal processes of the batteries should also be considered in defining the contribution of the electric vehicle to carbon dioxide emissions (and other regulated pollutants). Similarly fuels produced from biomass, such as corn ethanol, cannot be considered as carbon dioxide neutral since growing corn and production of ethanol consumes fossil fuels and hence emits $CO_2$. Such analysis is known as life-cycle analysis (LCA). LCA is a well-established methodology that accounts for the contribution of each stage or step in the chain of events that define a process, from beginning to end or from cradle to grave, in the effort to estimate its overall environmental impact. LCA is also used in economic assessment. The methodology is based on conducting careful material and energy balances over the chain of events that constitute the overall process, and applies methodologies of process analysis where a system boundary must be defined in the effort to assess the relationship between the input and output of the system. More examples of LCA analysis of energy conversion processes will be cited later, pointing out the importance of critical reading of data.

To put some of the emissions numbers in perspective, a power plant producing 500 MWe (megawatt electricity), running for

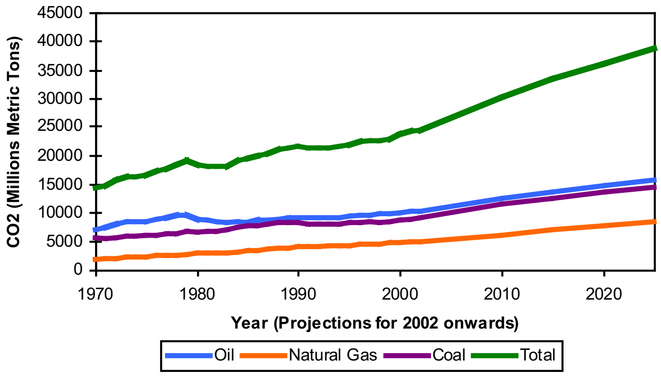

**Fig. 12.** Worldwide Energy related carbon dioxide emission, for the past three decades and projected for the next three, using current trends, in total and by fuel [12]. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

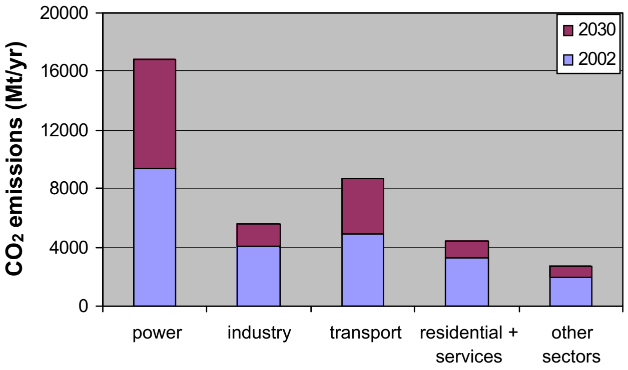

**Fig. 13.** Global carbon doxide emissions from fossil fuels in 2002, with forecast for 2030, classified by economic sector [11]. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

8000 h/y while burning coal, produces, on average, 4.8 $MtCO_2$/y (or 1.3 MtC/y). On average, coal fired plants produce almost 1200 $kgCO_2$/MWh, while natural gas fired plants produce 400 $kgCO_2$/MWh. This is because of the higher content of carbon in coal, and the higher thermodynamic efficiency of natural gas plants running on combined cycle instead of the typical simple cycle plants that burn coal. Coal power plants consume a fraction of their power in flue gas clean up processes to remove sulfur oxides, nitric oxides and ash. Given fuel prices and the wider availability of coal, the use of coal in electricity production has been rising, leading to increasing carbon dioxide emission in the electricity sector. The use of natural gas in the same sector has also been growing for a number of reasons. The higher price of natural gas as compared to coal is offset by the fact that power plants using natural gas are simpler if they use simple gas turbine cycles, and they achieve higher thermodynamic efficiency when the gas is fired in a more complex combined cycle plant. Coal burning produces ash and sulfur compounds that must be separated from the exhaust and disposed of. Natural gas is a clean burning fuel, easier to transport in pipelines and does not leave residues. Currently both fuels are used extensively in electricity production, the manufacturing industry, as well as residential services. The combined $CO_2$ production from both fuels constitutes the larger fraction of the total carbon dioxide emissions. Liquid fuels, on the other hand, are largely used in transportation.

Given the long lifetime of $CO_2$ in the atmosphere and the significant convection currents that circulate emissions in the Earth atmosphere, carbon dioxide emissions have not only local impact but also significant global impacts. Therefore, predicting future trends must consider rise in energy consumption patters worldwide. Carbon dioxide production in developing countries is expected to exceed that of developed countries in the next few decades because of several factors, including the expansion rates of their economies, the size of their populations, and the fuels available domestically [12]. This can be inferred from the actual and projected consumptions of fuels in developed (mature), transitional and developing (emerging) economies shown in Fig. 14.[17] As mentioned before, China's dependence on coal for electricity generation, heating and industrial production, and the production of liquid fuels is growing fast because of its growing economy and the vast coal resources available domestically. Recently China has surpassed the U.S. in total $CO_2$ production.

If the positive correlation between atmospheric concentration of $CO_2$ and the average global temperature persists, it could lead to a dangerous rise of atmospheric temperature by the end of the 21st Century. Current predictions indicate that stabilizing atmospheric carbon dioxide at the 550-ppm level and the associated temperature rise would be acceptable. Different scenarios that rely on improving energy conversion and utilization efficiency and using alternative energy sources have been suggested to reach but not exceed that limit in the near future [13]. In all these scenarios, the rate of rise of carbon dioxide injection into the atmosphere must be curtailed, the amount capped and then reduced. Towards this goal, energy conversion and utilization efficiencies must be improved, the use of zero-carbon sources including renewable sources and nuclear energy must be expanded, and mechanisms to capture carbon dioxide produced in power plants and fuel production facilities and to store it in geologic formations must be implemented. Given the scale and scope of the problem, it is unlikely that one single approach can work, and multiple approaches must be considered in parallel. Social and economic considerations are important factors in choosing among available options, and life-cycle analysis must be used in examining the true impact of the different strategies. Also, solutions that enable incremental transition to lower carbon emissions technologies, and/or further expansion of lower impact renewable resources, are more likely to succeed.

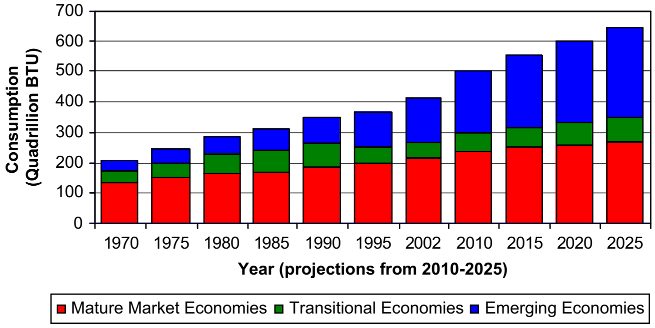

**Fig. 14.** Energy demand by economic status for the past three decades, and projections for the next three decades [12]. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

### 3.5. Global warming and climate change

More evidence is being cited for global warming, e.g., 19 of the warmest 20 years since 1860 have all occurred since 1980; 2005 was the warmest year since a record of the Earth temperature was kept and probably the warmest over the past 1000 years (based on estimates of the early years' temperatures that were inferred from tree rings and polar ice core). Data suggest that current temperatures are close to the highest values ever reached during the past 420,000 years, and that $CO_2$ concentration is even higher than the highest value estimated during this same period. The record of the temperature, carbon dioxide concentration, methane concentration and solar insolation are shown in Fig. 15. As shown in the plot, the temperature (in this case, the temperature at lake Vostok over the Antarctic), the atmospheric concentration of $CO_2$ and $CH_4$ varied cyclically during this period. However, the two quantities remained well correlated. It is interesting to note that the time scales for the rise and fall of the quantities of interest are different. At the scale of the plot, the rise seems to have occurred rapidly, while the fall occurred slowly. The figure shows that cyclic variation over the geologic time scales is the norm; current carbon dioxide levels are higher than the peaks reached previously. Prior to the onset of the Industrial Revolution in the mid 1800s, natural causes were responsible for carbon dioxide concentration variation as man-made emissions were negligible.

It is not easy to predict precisely the impact of global warming on life on Earth. For instance, while the average temperature is likely to continue to rise, thus extending the growth seasons of plants especially in northern latitudes, warmer temperatures may also support the spread and multiplication of pests that can destroy crops. Dry seasons may become longer and droughts may become more frequent in areas already known for their hot climate and desert topography. Some animal habitats may become endangered especially in colder climates. The impact of warmer temperatures on energy consumption is also unclear. More cooling and air conditioning may become necessary during longer warmer days, and less heat would also be required during the shorter cool seasons. Melting of glaciers and icecaps would make more land

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[17] OECD member countries are: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States.

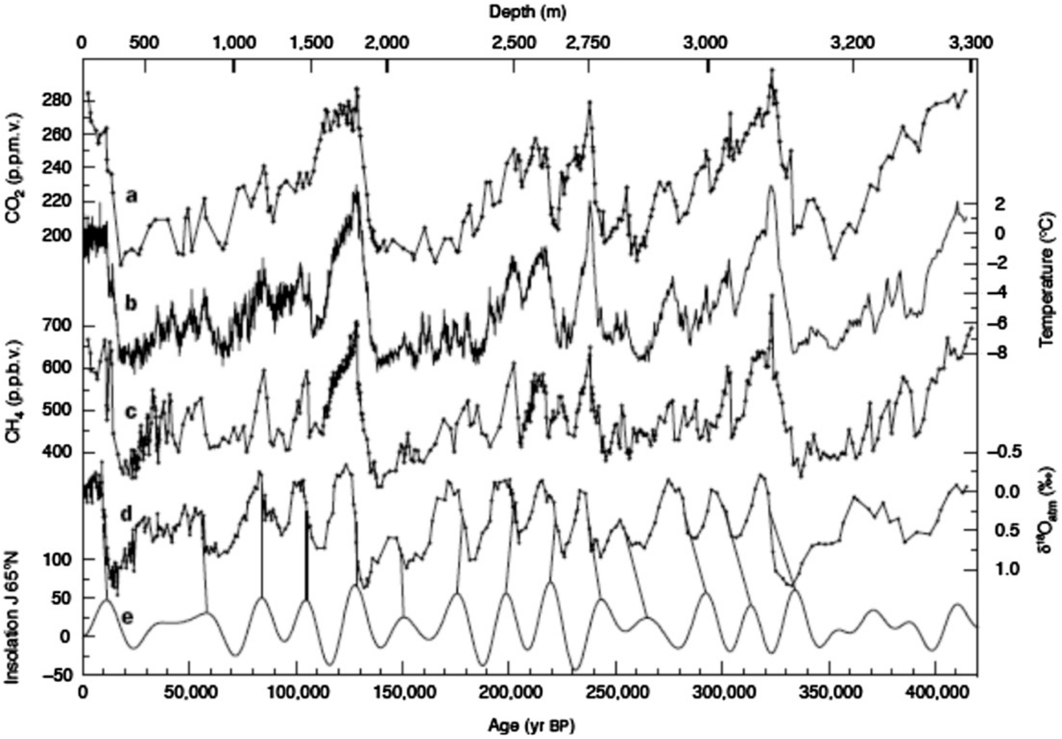

**Fig. 15.** Time series of (a) CO$_2$ concentration; (b) isotopic temperature of the atmosphere; (c) CH$_4$ concentration; (d); and (e) mid-June insolation at the given location in W/m$^2$. The top axis shows the depth of the ice sample and the bottom axis shows the age, Before Present. Source: Climate and atmospheric history of the past 420,00 years from the Vostok ice core, Antarctica, J.R. Petit, J. Jouzel, D. Raynaud, N.I. Barkov, J.-M. Barnola, I. Basile, M. Bender, J. Chappellaz, M. Davis, G. Delaygue, M. Dolmotte, V.M. Kotlyakov, M. Legrand, V.Y. Lipenkov, C. Lorius, L. Pepin, C. Ritz, E. Saltzman and M. Stievenard, Nature, 399, June 1999, 429–436. Fig. 3, page 431.

available for agriculture where it is currently not possible, but water runoffs and heavier rainfalls would damage the soil. Several of these changes, especially droughts and desertification, would impact poorer countries more severely, where adaptability and adjustment to substantial changes are less likely to be successful.

On the other hand, several major trends that could make strong impact on life on Earth have been suggested with reasonable confidence, including sea level rise, change of ocean acidity and increase in violent weather phenomena. These are discussed in more detail next.

### 3.5.1. *Sea level rise*

Sea level rise because of the melting of the polar ice caps, the receding glaciers and the thermal expansion of the ocean surface waters is an important result of global warming. Records of different geologic periods confirm that the rise and fall of the Earth's near surface temperature is associated with the same trend of the sea level. Estimates of sea level variation during the Twentieth Century indicate a rise of close to 20 cm from its levels in the Nineteenth Century, but actual values may be different because of the uncertainty associated with the techniques used in these estimates and measurements. Interestingly the melting of the glaciers and ice caps may contribute the least to the rise of sea level because of the balancing effect of increased evaporation. Most of the impact results from the warming of the surface layer of the ocean waters and the resulting volumetric expansion. Combined, it has been estimated that by the end of the century, with 1–2 °C rise in temperature, a 30–50 cm rise in sea level should be expected [14]. (It is estimated that if all glaciers and ice caps melt, sea level will rise by 50 cm, but the melting of Greenland and the Antarctic ice sheet, whose ice is mostly above sea level and would require millennia to melt, could lead to 68 m rise). Detailed calculations show a total rise of 0.387 m, attributed to 0.288 m of thermal expansion, 0.106 m from the melting of glaciers and icecaps, 0.024 m from melting in Greenland and 0.074 m from melting in Antarctica [15]. Estimates of sea level rise vary rather widely, depending on the melt models and the geometric ice volume models, and how volume shrinkage is treated. These melt models feed into a global mass balance to account for the net impact of melting, evaporation and precipitation, and are coupled with radiation-forcing models to compute atmospheric temperature variation with regional adjustment. The coupled model is run on a reasonably resolved global grid to predict the sea level rise.

Sea level rise will have devastating impact on coastal area, especially agricultural land in the Southern US, India and Bangladesh, and Egypt, as shown in Fig. 16.[18]

### 3.5.2. *Change of ocean acidity*

Carbon dioxide absorption in the ocean lowers its pH levels, making it more acidic and impacting near surface organisms as well as those living deeper. The current average ocean water pH is 8.2. It is estimated that the rise in atmospheric CO$_2$ has already lowered the acidity by 0.1 from the pre-industrial levels. Ocean circulation models used in these studies include weathering of carbonate and silicate minerals on land, production of shallow water carbonate minerals, production and oxidation of biogenic organic carbon, production and dissolution of biogenic carbonate minerals on the ocean, air-sea gas exchange of carbon and transport of all species by advection, mixing and biological processes. These models predict a pH reduction of 0.7 units over the coming centuries if the current rise in carbon dioxide continues according to the business as usual scenario, and until fossil fuels are exhausted (leading to more than

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[18] For more detail see http://www.cresis.ku.edu/research/data/sea_level_rise/index_html.

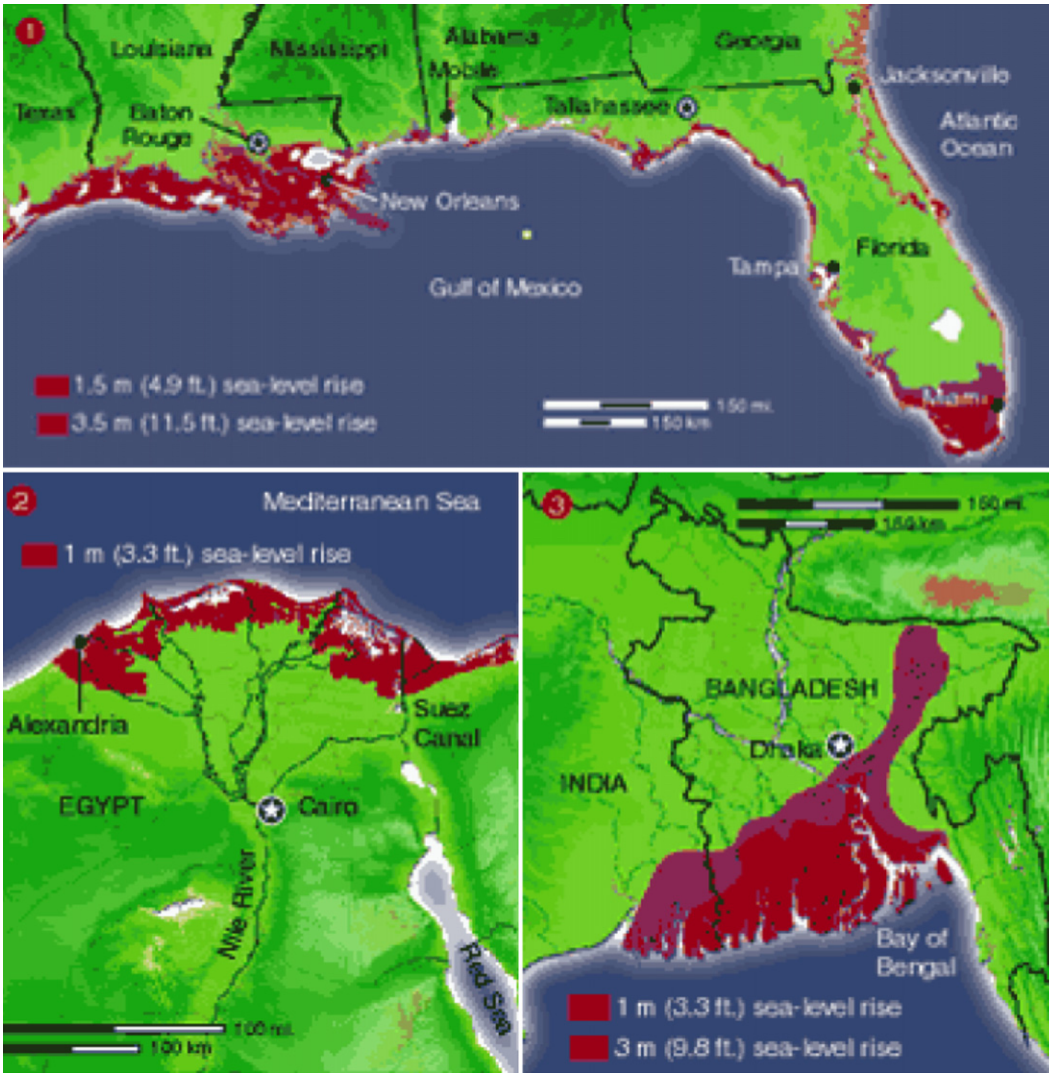

**Fig. 16.** Estimates for flooded areas due to predicted sea level rise in the southern US, northern Egypt and Bangladesh. http://www.cresis.ku.edu/research/data/sea_level_rise/index_html. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

1900 ppm in the atmosphere by 2300). There is no record that ocean pH level ever dropped below 0.6 units lower than their levels today. Carbon dioxide solubility in water increases at lower temperatures and higher pressures. Thus, $CO_2$-related acidity rise might increase at deeper water levels, affecting acidity-sensitive corals including strong reduction in calcification rates. The negative impact of higher acidity would compound the negative impact resulting from rising water temperature alone (which lowers $CO_2$ solubility) as that further changes the ocean chemistry and the response of the bio-organisms. While the full impact of these changes is still under investigation, and it will be centuries until this effect is fully observed, coral reef, calcareous plankton and other organisms whose skeleton or shells contain calcium carbonate may be endangered sooner [16]. Higher water temperature has been shown to lead to bleaching of coral, killing the living organisms and leaving behind only their calcium carbonate skeleton.

### 3.5.3. Changes in weather phenomena

With warmer temperatures, on average, a more temperate climate will extend to higher latitudes, and extended periods of rain may occur due in part to the higher water concentrations in the warmer atmosphere. Hurricanes and typhoons, spawned by waters warmer than 27 °C within a band from 5 to 20° north and south latitude, may occur more frequently. Ocean currents, such as the Gulf Stream and the Equatorial currents, which are driven by surface winds and density differences in the water, could also become more frequent and violent. Some of these currents can be accompanied by phenomena that cause strong weather perturbations. For instance, El Nino, which arises because of westward wind-driven surface water currents from the South American coast and sets up ocean circulation in which upwelling of colder water replaces the surface warmer waters, is known to increase the frequency of hurricanes and heavy storms. Fig. 17 shows the change in the total power dissipated annually by tropical cyclones in the north Atlantic (the power dissipation index, PDI) and the September sea surface temperature (SST) for the period of 1930–2010. A substantial and dangerous rise in the PDI is observed since the early Nineties, along with the SST [17].

### 3.5.4. Regional impact

Studies of the local/regional impact of global warming on climate change demonstrate the difficulties of determining with certainty the likely consequences of changing the temperature, but

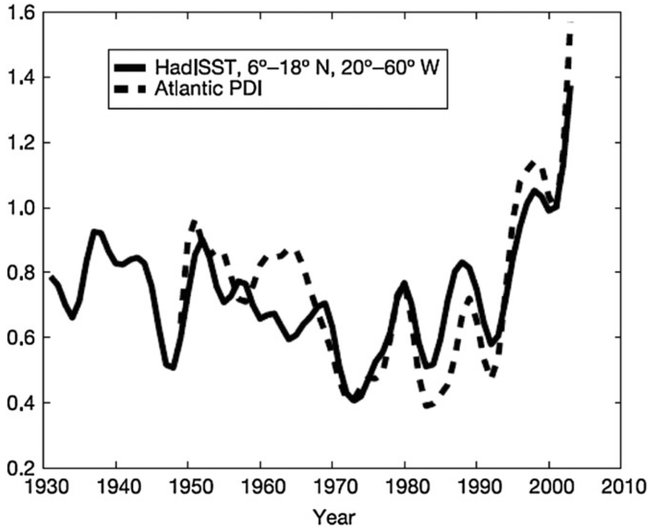

**Fig. 17.** A measure of the total power dissipated annually by tropical cyclones in the north Atlantic (the power dissipation index PDI) compared to the September sea surface temperature (SST) [17], measured over the past 70 years. The PDI has been multiplied by 2.1 x $10^{-12}$ and the SST is averaged over 6–18 N latitude and 20–60 W longitude. North Atlantic hurricane power dissipation has more than doubled in the past 30 years.

also the urgency for immediate action given the potential dangers. For instance, Hayhoe et al. [18] conducted a modeling study to determine the impact of the rise of carbon dioxide levels to 550 ppm (which are likely to be reached even with aggressive intervention) or 970 ppm (the level likely to occur in the absence of mitigation policies) by the end of the 21st century on the state of California. Focusing on a small region allows the computational models to use finer grids while solving the governing equations, and hence achieves higher predictive accuracy. However, applying the predictive models to predict regional scenarios requires the application of complex downscaling and rescaling methods to relate data and predictions at different scales and with different resolutions, between the global and the local levels. Statistical methods are often used for this purpose, given the nature of weather phenomena and the probabilistic approaches used in their description. The California study shows that by the end of the century:

- Statewide temperature would rise by 2.3–5.8 °C (from current average of 15 C), with higher values predicted for the summers and under the higher emissions scenario.
- This rise would be associated with more heatwave days (rise of 50–600% in extreme cases) and longer heatwave seasons.
- Heatwave mortality in LA would rise by a factor of 2–7.
- Although one extreme low emissions case showed a rise in annual precipitations, others showed up to 30% decrease, and with a drop of 30–90% in the Sierra Nevada Mountains snowpack.
- Accordingly, annual reservoir inflow would also decrease.
- Substantial loss in alpine and subalpine forests, ranging from 50 to 90% of their current size, was predicted.

The study concludes by stating that: *Declining Sierra Nevada snowpack, earlier runoff and reduced spring and summer streamflows will likely affect surface water supply and shift reliance to ground water resources, already overdrafted in many agricultural areas in California.* Significant impact on agriculture and the dairy industry follow.

### 3.6. The UN and Kyoto agreement

In response to these potential threats, several actions have been suggested and some have been taken. Worthwhile mentioning here is the United Nations Framework Convention on Climate Change (UN-FCCC), which was signed in 1992, whose ultimate objective was to achieve stabilization *of greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved in such a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner* [19]. Several years later and following intensive debates and deliberation in the UN conference on climate change, the Kyoto agreement was proposed in 1997. The Kyoto agreement called for the reduction of $CO_2$ emissions to levels 5.2% below 1990 level by 2008–2012. The agreement was supposed to be enforced by 2005, but that did not happen. The agreement would have primarily impacted the developed countries, requiring 12.5% carbon dioxide reduction in the UK, 8% reduction in the EU, 6% reduction in Japan and 7% reduction in the US. Energy conservation efforts and technologies to enable reducing carbon dioxide emissions, some of which will be reviewed in the next few sections, were proposed. Although some measures have been taken towards limiting $CO_2$ emissions, including considering some form of tax on carbon dioxide emissions as well as a cap-and-trade system for carbon dioxide in some countries, the Kyoto agreement was never enforced and the target reductions are very unlikely to be achieved voluntarily in the near future. A combination of economic concerns and technological hurdles must be overcome before steps can be taken in that direction. A global vision supported by a political will in the major industrialized countries are prerequisites for implementation of carbon dioxide emissions reduction strategy.

Without intervention, $CO_2$ concentration in the atmosphere will continue to rise. The plot in Fig. 18 [13] shows the total yearly carbon dioxide injected into the atmosphere over the past decade, measured in terms of GtC, and the projected rise in the same quantity according to two different scenarios. The first scenario is evaluated according to the projected $CO_2$ emissions assuming the continued rise in energy consumption without much change in the energy source mix, i.e., following the business as usual (BAU) trends described early. The other scenario would follow a trajectory in which $CO_2$ annual emissions would be slowed down, capped around their values around the year 2030, then reduced gradually

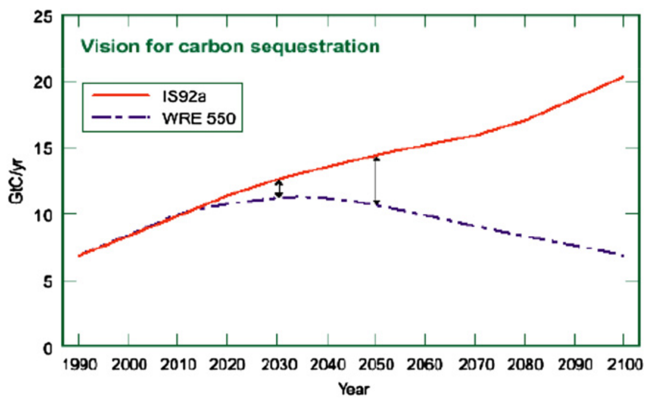

**Fig. 18.** Total global carbon emissions worldwide under two scenarios: business as usual (according to the IS92a), that is extrapolating data for continuing rise of $CO_2$ concentration, and WRE550, which caps carbon dioxide concentration to 550 ppm [13]. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

until the end of the century to values closer to the current carbon dioxide injection rates. Reduction of carbon dioxide emissions from the BAU to those that would return to current values by the end of the 21st century, without negatively impacting economic growth or quality of life, require significantly improved conversion and utilization efficiency, the use of zero-carbon sources such as nuclear and renewable energy, and the separation of $CO_2$ from combustion products and its storage in deep reservoirs. Some of these strategies and associated technologies are described briefly in the following section.

## 4. $CO_2$ emissions mitigation

The previous discussions show that continuing the process of releasing more energy-related $CO_2$ into the atmosphere may pose a serious and irreversible risk. Meanwhile, the current energy infrastructure is predominantly dependent on fossil fuels, and changing this infrastructure can only happen gradually, over many decades and at substantial investment. Depending on the alternative energy sources and technologies, other environmental costs should be considered. It is very likely that carbon dioxide reduction will have to be achieved as we continue to use fossil fuels as a primary energy source for several decades while alternatives are being introduced and integrated into our energy infrastructure. Four major approaches to accomplish this task have been proposed, and are list below:

1. Improving the efficiency on the supply side, i.e., improving conversion efficiency from the raw sources to the useful form or end product, e.g., raising the efficiency of electricity generation power plants, vehicle engine and transmission, light bulbs, and other devices that convert energy from one form to another.
2. Improving the efficiency on the demand side, that is, on energy utilization side through better building insulation, using natural heating and cooling, expanding public transportation, introducing higher efficiency appliance, etc. This effort also requires better city planning, more efficient agricultural practices, lower water use, etc.
3. Reduced dependence on high carbon fuels by switching from coal to natural gas or other low C/H fuels, expanding the use of nuclear energy and much more reliance of renewable sources including solar and geothermal sources for heat and electricity, some forms of biomass for fuel and electricity production, and wind and wave energy for electricity.
4. Carbon dioxide capture and sequestration (CCS) from power plants burning heavy hydrocarbons, directly by injecting $CO_2$ produced in such plants in deep reservoirs or reacting it into stable disposable chemicals, and indirectly using biological approaches, such as growing trees and algae.

The four approaches presented above will be discussed in some detail next, along with estimates of their impact on $CO_2$ emission and the conversion system efficiency when appropriate. Given the scale of energy utilization and associated $CO_2$ emission, a portfolio of technological solutions will be required to address the challenge of reducing the rate of carbon dioxide accumulation in the atmosphere within the next 50 years. Perhaps the most unusual approach here is the last, that is, CCS in underground geologic formations. Carbon dioxide capture from power plants burning fossil fuels adds technical complexity to the power (or fuel production) plant, increases its capital and operating cost and reduces its thermodynamic efficiency. As will be shown, the efficiency penalty depends on the fuel and how the plant design is modified to enable $CO_2$ capture. Geological sequestration adds another energy and efficiency penalty associated with the transportation of liquefied carbon dioxide from the production site to the storage site and its injection underground. Several storage sites have been proposed, including depleted oil and gas reservoirs, geologic formations such as deep saline aquifes, coal seams, solid mineral carbonates, and even underwater in the deep oceans. The latter has been discounted recently, and the focus has shifted to underground options. Injection of $CO_2$ into oil wells is already being practiced at small scale for enhanced oil recovery. Biological sequestration using reforestation and growing certain types of algae is another option. However, this sink has limited capacity, and decaying biomatter eventually releases their carbon dioxide into the atmosphere (unless it is deeply buried).

Multiple sequestration strategies in high-capacity reservoirs have been identified, and studies as well as small-scale experiments are underway to examine their long-term potentials. The major reservoirs and their estimated capacity are shown in Fig. 19, and several projects/experiments, with total capacity of 30 $MtCO_2$/y, are currently underway to test this concept [20,21]. For comparison, the IPCC estimates that the total cumulative 1990–2100 emissions of $CO_2$ from fossil fuel burning using business as usual global energy consumption scenario (IS92a) is 1500 GtC. Moreover, the carbon content of “all” remaining exploitable fossil fuels, excluding methane hydrates, is estimated to be 5000–7000 GtC. Moreover, current work to capture $CO_2$ in the coal gasification power plant in North Dakota and inject it in the Weyburn field in Canada for enhanced oil recovery (EOR) targets 1.5 $MtCO_2$/y. Another project, where $CO_2$ is being separated from the outflow of a natural gas well and is injected back deep underground is the Sleipner field in Norway. This project targets less than 1 $MtCO_2$/y. Carbon dioxide injection is also used for enhanced methane recovery from coal beds in the Juan basin in the US, and several more fields in Canada where acid gas ($H_2S + CO_2$) is injected to recover sour natural gas (NG).

Sequestration in the form of solid carbonate minerals has also been proposed. One approach is to use the exothermic reaction between forsterite ($Mg_2SiO_4$) and $CO_2$, which is favored under ambient conditions, to form $MgCO_3$ (serpentine $Mg_3Si_2O_5(OH)_4$). While there are abundant reservoirs to store all the expected-to-be-emitted $CO_2$ in the form of carbonate carbon, and the method is safe, it requires large amount of material to be transported and processed making it rather expensive. Clearly, sequestration by

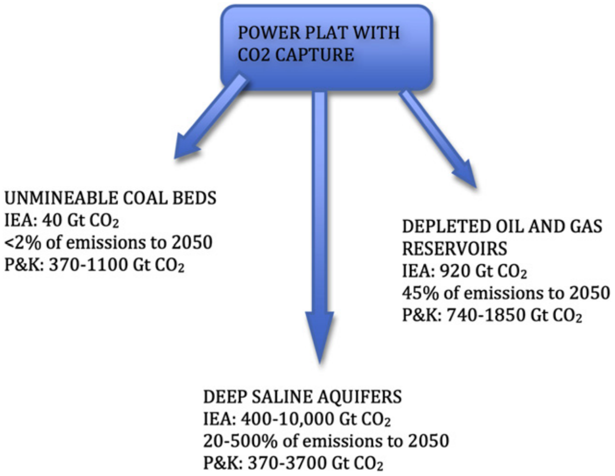

**Fig. 19.** Carbon dioxide sequestration capacity in coal beds, depleted oil and gas reservoirs and deep saline aquifers, as estimated by the IEA [20] and a study by Parson and Keith (P&K) [21]. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

itself cannot achieve the desired goal for $CO_2$ reduction in the next decades, and effort on multiple fronts, such as achieving higher overall conversion and utilization efficiency, more extensive use of renewable and nuclear resources, and forestation are necessary.

### *4.1. Implementing multiple solutions*

Carbon dioxide emissions reduction scenarios using multiple approaches that would be implemented in parallel to achieve the overall goal have been suggested, domestically and at the global scale. Given the magnitudes of $CO_2$ currently being produced, the anticipated rise in the emission rate and the inertia of the system against rapid change, it is highly unlikely that a single solution can be scaled up to be sufficient. Moreover, contrary to other regulated pollutants such as CO, $SO_2$ and $NO_x$, which impact the local and regional environment, carbon dioxide footprint is global, and global solutions must be suggested, agreed to and pursued on that global scale. For instance, Fig. 20 shows a trajectory that would limit $CO_2$ emissions in the U.S. to the 2001 level by the year 2050, achieving the goal using several approaches in parallel [22]. Nearly 50% of the emission reduction may be achieved by capturing $CO_2$ from power plants and $H_2$-production plants. The other 50% reduction might come from improved efficiency (conversion and utilization) and the accelerated introduction of renewable and other carbon-free sources. A small fraction in carbon dioxide reduction results from expanding natural/biological $CO_2$ sinks, such as reforestation. Other similar strategies for carbon dioxide management have been suggested in other parts of the world.

### *4.2. The wedges*

Pacala and Socolow [23] describe a scenario for achieving the goal of stabilizing atmospheric carbon dioxide concentration at the 550 ppm level by 2050 using existing technologies, but with some radical changes on how extensively some of these technologies are deployed. Atmospheric modeling shows that the objective of reaching this level of $CO_2$ concentration could be achieved by holding carbon dioxide emission at 7 GtC/y over the next 50 years. The BAU rate of increase of 1.5% per year would double the rate of emissions to 14 GtC/y by the year 2050. The authors discuss a number of solutions to achieve this reduction; each one would prevent the emission of 1 GtC/y by mid century. Note for reference that 1 GtC/y is produced by a 750–800 GW coal power plant at the current average efficiency of 34%, or a 1500–1600 GW NG power plant at the current average efficiency of 46%. Each of the different solutions is expected-to-be-deployed gradually, reaching full maturity in 50 years, but must start immediately to have the desired effect. They divide the different solutions among four categories:

- Improved conversion and utilization efficiency,
- Shifting the fuel to lower carbon content,
- CCS; and
- Deployment of renewable resources.

Fig. 21 [23] shows the overall strategy, represented by seven “wedges”, each leading to the reduction of carbon dioxide emission by 1 GtC/y by the year 2050. Deploying seven solutions should lead to the desirable goal of stabilizing the carbon dioxide emission rate at 7 GtC/y.

The following tables summarize some of the proposed solutions, and the necessary implementation strategy to make each proposed solution successful and effective. The solutions are divided by categories including improved conversion efficiency in power plants, and utilization efficiencies in building and in the transportation vehicles, shifting to lower carbon-content fuels such as natural gas instead of coal, capturing carbon dioxide emitted from fossil fuel power plant and storing it, doing the same in hydrogen production plant that use fossil fuel as a feedstock, using nuclear energy for electricity and hydrogen production, and significantly expanding the use of renewable energy. Several messages can be gleaned from this table. All options are available for deployment, if the will exits, the economic incentive is offered and the engineering is scaled up to the levels indicated. All options require large-scale efforts, starting with the best available technology but moving forward to scale up the implementation, making them economically viable across the World, and adapt the different options to different conditions. Given the challenges of scaling up a technology that defines a single wedge to the size required to achieve the objective, it is likely that more than seven different solutions must be deployed in parallel. Also some options still need proof of concept, such as carbon capture and sequestration at the necessary scale, while others pose particular technology challenges such as using hydrogen extensively in the transportation fleet. In many cases, applying the technology at scale is a question of building up the infrastructure to support its needs. Some solutions are interdependent, such as hydrogen production from fossil fuels with CCS,

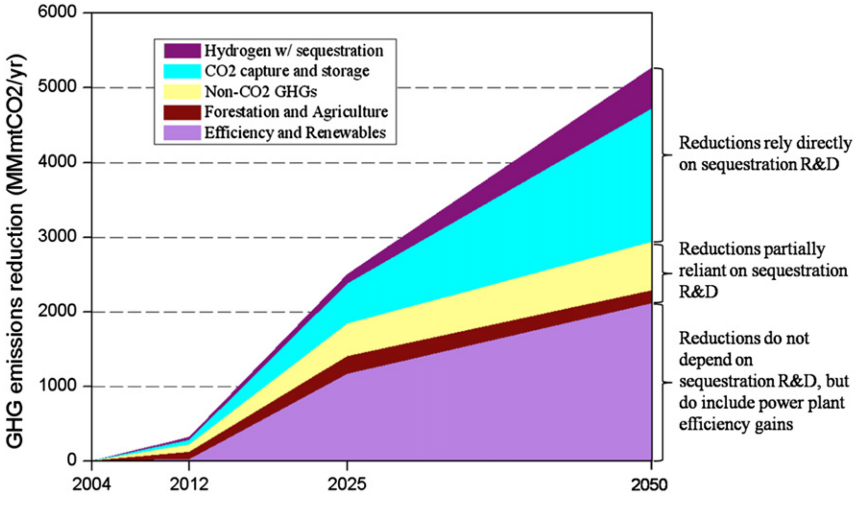

**Fig. 20.** Approaches for reducing $CO_2$ emission, to be implemented in parallel, including capture from power plants and $H_2$-production facilities, and deployment of nuclear and renewable energy production [22]. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

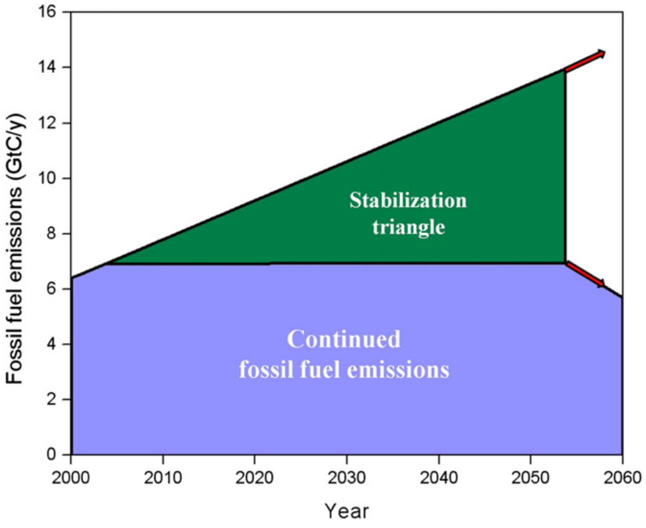

**Fig. 21.** (Taken from Pacala and Socolow [23]). The top curve shows the rise in the yearly $CO_2$ emission following a business as usual scenario in energy sources and cement manufacturing. The bottom curve shows an emission path that leads to stabilizing emissions at 7 GtC/y. The difference between the two curves is divided into 7 "wedges" each enabled by one of the options described in Table 1. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

to be used next for transportation. Meanwhile, expanding the use of natural gas in electricity generation as a substitute for coal would impact its availability as a feedstock for hydrogen production for transportation. Current hydrogen production, which relies primarily on steam reforming of methane, would need to be scaled up by an order of magnitude to satisfy the requirement on one wedge, and the resulting $CO_2$ would have to be captured (at the requisite pressure and temperature) and stored underground. The challenge of scale can be appreciated from the following two examples: Current rates of $CO_2$ injection deep underground, used primarily for enhanced oil recovery (EOR), will have to be scaled by two orders of magnitudes to satisfy the needs for one wedge. For synthetic fuel production, that is the production of liquid fuel from coal and other heavy hydrocarbons, the maximum capacity of the largest of such plants is that of Sasol of South Africa, which produces 165,000 bpd (barrel per day) of liquid fuel from coal. A wedge would require 200 Sasol-scale plants with CCS.

The challenges are not any less daunting when we consider the expanded use of carbon-free sources such as nuclear energy, biomass energy, solar and wind sources. Note for instance that currently the production of biofuels, especially in the developed industrialized world, uses significant amounts of fossil fuels in mechanized agriculture, the production of fertilizers, the transportation of the feedstock from the location of the harvest to the fuel production plant, and in fermentation and distillation of the fuel. In some estimates, the same amount of energy available in ethanol produced from corn is consumed in its production [24]. If fossil fuels were to be replaced by biofuels in the transportation sector, the need for land, water, fertilizers, etc., would rise significantly, and the associated ecological impact could be devastating, let alone its impact on food prices. Similarly, energy is used in the fabrication of wind turbines, their installation and maintenance, as well as in photovoltaic cells (PV). To reach the capacity required for a single wedge, we will need 700 times the current installed capacity of PV, and that does not consider the need for storage and the associated loss of efficiency during storage and recovery of energy in batteries. The production of hydrogen using renewable sources would be even more energy intensive if the energy required for transportation and storage of this light fuel is taken into consideration. Other technologies are not mentioned in the table, but could have similar impact on improving conversion and utilization efficiency. These include, e.g., thermoelectric conversion, which can take advantage of waste heat to produce electricity (tailpipe thermal energy). Some are even more futuristic, such as space based solar power [25].

The study of Pacala and Socolow also considers carbon dioxide sinks that can be expanded by reducing deforestation, as well as the reforestation of clear-cut forests especially in tropical areas. These solutions are not shown in the table but are discussed in their paper. They estimate that one half wedge would be created by reforesting near 250 million hectares in the tropics or 400 million hectares in temperate zones (current areas of tropical and temperate forests are 1500 and 700 million hectares, respectively). Better agricultural practices that reduce the decomposition rate of organic matter could also contribute to reducing the loss of soil carbon. The impacts should be considered temporal, since decomposition is inevitable.

We should mention here that the overall impact of each solution and its contribution to $CO_2$ reduction varies geographically, and the best approaches to using the available sources and technologies depend on the time and location where they are applied. Also, some lower efficiency solutions might be preferred because they may be more compatible with practical needs. For instance, two scenarios for the utilization of solar energy in transportation: electric vehicles and hydrogen based fuel cell vehicles. On an overall life-cycle analysis basis, the efficiency of electric vehicle, requiring solar electricity generation, storing the electricity in batteries and using this energy to power the vehicle is higher than that of the fuel cell vehicle which needs the conversion of solar energy to electricity to hydrogen (via electrolysis), then converting back the hydrogen to electricity (via fuel cells). Thus the first approach should be used if the overall best efficiency is the ultimate target. On the other hand, practicalities, such as the low energy density of current batteries, which limits the range of an all-electric vehicle, may favor the lower efficiency solutions of the hydrogen fuel cell vehicle. Of course, the second solution assumes the availability of practical hydrogen storage technology for long distance driving, which is still a challenge, as mentioned previously.

### 4.3. Renewable sources and energy storage

Expanding the use of renewable energy sources requires substantial improvement in high energy-density storage technologies and a similar reduction in their cost and in some cases environmental impact. Renewable energy sources are characterized by large intermittency or interruptability on scales spanning:

- Hours to days for solar and wind sources;
- Seasons for solar, wind, biomass, hydro and some forms of geothermal; and,
- Longer periods for some forms of fossil fuels.

Without significant storage capacity, back-up power is required for dispatchibility, that is, for having access to continuous power as source availability is reduced and the load varies. The challenge here is to purse one of several options including the following:

- Expanding the use of high-capacity batteries in case wind or photovoltaics are used to generate electricity. Batteries store energy in the form of chemical energy and have high two-way (round trip) energy conversion efficiencies. Battery technologies have progressed with the expanded use of lithium ion batteries, although advanced batteries are used primarily in hand-held devices. Flow batteries are more suitable for large-scale stationary power applications. Other electrical energy storage devices include: Supercapacitors that store energy in the form of confined electric charge, and superconductors, in which electromagnetic energy is stored in a cooled superconducting coil. Similar to batteries, the application of these devices is currently limited to portable or mobile devices;

- Expanding the use of thermal energy storage in molten salts or solids and other high heat capacity media, or via phase change, in case the source can be harnessed in the form of thermal energy. Thermal energy storage has been used with concentrated solar thermal plants to extend their operation several hours beyond sunset. Other “thermal” energy storage solutions included the production of ice and liquefied natural gas;
- Developing high-capacity compressed air storage containers or underground sites, located close to renewable energy sources. These are most compatible with storing wind, wave or solar energy that has been converted to electricity in places where water reservoirs are not available. Underground sites that can be exploited for this purpose include salt cavities, aquifers and cavities with compensating surface reservoirs. Although this approach has not been exploited widely it is flexible and can be hybridized with fossil fuels;
- Constructing high-capacity pumped-hydro storage facility to store potential energy generated by hydro-dams or other mechanical or electrical energy generation facility. These are relatively affordable energy storage solutions;
- Large-scale flywheel for direct storage and recovery of kinetic energy;
- Developing and implementing high efficiency conversion technologies, such as electrolysis, to convert electricity to chemical energy storage forms, such as hydrogen. This requires the development of efficient high-capacity hydrogen storage technologies, such as efficient compression or liquefaction, and affordable storage media.

As an energy carrier, hydrogen can be used to generate mechanical energy in engines, or electrical energy in polymer-electrolyte membrane (PEM) fuel cells. “Reversible” or two-way PEM fuel cell/electrolyzer have been designed for hydrogen production and utilization, thus by reducing the hardware cost. It should be mentioned, however, that considering the efficiency in each conversion step, the “round trip” efficiency, that is, the overall efficiency from electricity (produced from solar or wind) back to electricity (produced in the fuel cell) is rather low. The cost of this system can also be high because of the reliance of PEM fuel cells and electrolyzers on platinum catalysis (it is estimates that 10 TW equivalent of hydrogen flow rate through this reversible hydrogen generation and utilization system would require 30 times today’s worldwide platinum production). The use of solar thermal electric power plants simplifies short-term storage since these systems can store thermal energy in high heat capacity materials such as molten salt, which can be used later in running the same power plant.

Large-scale higher capacity storage options include pumped-hydro plants and compressed air plants. Compressed air storage is compatible with wind energy; the wind electricity is used to run compressors to pump air in underground high-pressure air storage facilities. Pressurized air can be stored in underground reservoirs in rock or salt cavities or in naturally contained porous aquifers. When needed, the high-pressure air can be used to power air turbine to produce electricity. The system can be hybridized with fossil fuels, i.e., fuel can be burned in the compressed air to raise its temperature and a gas turbine can be used instead of the air turbine to produce more power. Pumped-hydro storage is used extensively because of its simplicity in places where natural or man-made large water reservoirs are available and where the natural topography can help. Table 2 describes a number of storage options, available or under development, for mobile and stationary applications. The table does not show the chemical storage options, that is, hydrogen

**Table 1**

Carbon dioxide reduction through efficiency improvement, fuel shift, $CO_2$ capture and sequestration, and the utilization of nuclear and renewable energy sources. Table is summarized from that in Pacala and Socolow [23].

| Option | Technology solution | Needs |
|---|---|---|
| *Improved conversion and utilization efficiency* | | |
| 1. Efficient vehicles | Raise fuel economy for 2B cars from 30 to 60 mpg | Novel engine options, reduced vehicle size weight and power |
| 2. Less use of vehicles | 2B cars @ 30 mpg travel 5000 instead of 10,000 m/y | Expand public transit options |
| 3. Efficient buildings | 1/4th less emissions: efficient lighting, appliances, etc. | Insulations, efficient lighting, passive solar, environmentally guided design. |
| 4. Efficient coal plants | Raise thermal efficiency form 32% to 60% | Technical improvement in gas separation, higher temperature gas turbines, etc. |
| *Fuel shift* | | |
| 5. NG instead of coal for electricity | Replace 1.4 TW coal (@ 50%) with gas (4 × current NG plant capacity | Lower prices of NG |
| *Capture $CO_2$ (CCS)* | | |
| 6. In power plants | CCS in 0.8 TW coal or 1.6 TW gas (>3000 time Sleipner capacity) | Improved technology of separation and sequestration |
| 7. In $H_2$ production for transportation | CCS in coal producing 250 $MtH_2/y$ or NG plants producing 500 $MtH_2/y$ (10 × current $H_2$ production from NG) | Technology and $H_2$ issues |
| 8. In coal to Syngas plants | CCS in plants producing 30 Mbarrel/day (200 × current Sasol capacity) from coal | Technology and price of synfuels |
| *Nuclear energy* | | |
| 9. Nuclear instead of coal for electricity | 700 GW fission plants (2 × current capacity) | Security and waste |
| *Renewable sources* | | |
| 10. Wind instead of coal for electricity | Add 2 M 1-MW peak turbines (50 × current capacity) ($30 \times 10^6$ ha, sparse and off shore) | Land use, material, off shore tech. |
| 11. PV instead of coal for electricity | Add 2 TW peak PV (700 × current capacity) ($2 \times 10^6$ ha) | Cost and material |
| 12. Wind for $H_2$ (for high efficiency vehicles) | Add 4 M 1-MW peak turbines (100 × current capacity) | $H_2$ infrastructure |
| 13. Biomass for fuel | Add 100 times current Brazil (sugar cane) or US (corn) ethanol. ($250 \times 10^6$ ha. 1/6 of total world cropland) | Land use |

**Table 2**
Energy Storage Technology Characteristics, original sources: Jensen, J., and B. Sorensen. 1984. Fundamentals of Energy Storage. New York, Wiley, Schoenung, S., J.M. Eyer, J.J. Iannucci and S.A. Horgan. 1996. "Energy Storage for Competitive Power Market." Annual Review of Energy and the Environment. 21: 347–370, and Boes, E.L., L. Goldstein and G. Nix 2000. "Energy Storage and Overview", Working Paper. Golden, C.: National Renewable Energy Laboratory.

| Characteristic | Pumped hydro | CAES[a] | Flywheels | Thermal | Batteries | Super-capacitors | SMES[b] |
|---|---|---|---|---|---|---|---|
| Energy range | $1.8 \times 10^6$–$36 \times 10^6$ MJ | 180,000–$18 \times 10^6$ MJ | 1–18,000 MJ | 1–100 MJ | 1800–180,000 MJ | 1–10 MJ | 1800–$5.4 \times 10^6$ |
| Power range | 100–1000 MWe | 100–100 MWe | 1–10 MWe | 0.1–10 MWe | 0.1–10 MWe | 0.1–10 MWe | 10–1000 MWe |
| Overall cycle efficiency[c] | 64–80% | 60–70% | ~90% | ~80–90% | ~75% | ~90% | ~95% |
| Charge/discharge time | Hours | Hours | Minutes | Hours | Hours | Seconds | Minutes to hours |
| Cycle life | ≥10,000 | ≥10,000 | ≤10,000 | ≥10,000 | ≤2000 | >100,000 | ≥10,000 |
| Footprint/unit size | Large if above ground | Moderate if under ground | Small | Moderate | Small | Small | Large |
| Siting ease | Difficult | Difficult to moderate | N/A | Easy | N/A | N/A | Unknown |
| Maturity | Mature | Early development | Early development | Mature | Lead acid mature, others under development | Available | Early R&D Stage, under development |

[a] CAES = Compressed Air Energy Storage.
[b] SMES = Superconducting Magnetic Energy Storage.
[c] For 1 full charge–discharge cycle.

and other synthetic fuels that can be formulated using renewable electricity or thermonuclear energy. Some analysts also consider biomass as an energy storage option (storing solar energy through photosynthesis in plant material). The potential for chemical storage will be discussed briefly later, in the context of transportation. It should be mentioned that large-scale storage technologies have environmental footprints that should not be ignored in evaluating their performance, such as the toxicity of battery chemicals, and the land use in hydro and air storage projects. Small scale, high energy and power density energy storage technologies, such as batteries, supercapacitors and flywheels, are important for hybrid power trains for transportation. These will be revisited in the section on transportation. Storage adds to the cost of utilization of renewable energy, and should be factored in when large-scale renewable energy projects are planned. Hybridization with fossil fuels, whenever possible, should be considered as an alternative.

### 4.4. Note on efficiency

Efficiency is a complex concept and can be defined in many forms. On the conversion side, the definition follows simple but definitive forms, such as the usable energy output from a given process or system, as a fraction of the input energy to the system. In fossil energy systems, the input is the chemical energy stored in the molecular bond of a fuel, defined more precisely as a chemical energy carrier. The output might be the chemical energy in another carrier (following a process of refining or reforming); the thermal energy (or heat in combustion); the mechanical energy from the engine; the electrical energy from a generator; the electrical energy from batteries and fuel cell, etc. Depending on the system, one or multiple conversion processes, each with its own efficiency, may have to be considered, with the overall efficiency being the product of individual efficiencies. In nuclear energy, the source is the atomic bond energy, and one or multiple conversion processes, that is, nuclear to thermal, thermal to mechanical, mechanical to electrical, etc., may be considered depending on the output. In renewable systems, similar efficiencies are defined between the source flux (solar energy, wind energy, geothermal energy, etc.) and the output, which might be electrical, chemical, mechanical, etc. Real energy conversion processes involve dissipation and losses, and the Second Law of Thermodynamics limits the efficiency of all conversion processes to less than 100%, whether they rely on the traditional "heat engine" in the case of thermal to mechanical energy conversion, or other concepts. Most processes have theoretical efficiency limits that cannot be exceeded, e.g., the Carnot efficiency in heat engines, even under "equilibrium conditions". There may also sources of inefficiency imposed by other considerations outside the "equilibrium limit" such as finite-rate processes including kinetic and transport overpotentials in fuel cells, as well as from real hardware characteristics. The difference between the theoretical and actual efficiencies represents the opportunity for improvement, which might come at the expense of more system complexity or with technological innovation.

For instance, while the Carnot efficiency of heat engines (mechanical energy divided by heat input) are near 70–80% depending on the temperatures of the heat source and sink, real gas turbine and steam turbine cycle efficiencies are 35–55% (simple and combined cycles). For IC engines, actual efficiencies range from 15 to 45% (in spark ignition engines vs. diesel engines). Note however that engine efficiency has a different definition than that of a heat engine; the engine efficiency is the mechanical energy output of the engine divided by the chemical energy of the fuel. That definition accounts for combustion efficiency, heat losses and friction. Fuel cell efficiencies are higher than those of most engines, typically in the range of 40–60% for the electrical energy output divided by the fuel chemical energy.[19] However, the fuel cell efficiency depends strongly on the power density. Battery efficiency is higher than that of a fuel cell, reaching close to 90% for electrical to chemical (charging) and for chemical to electrical (discharging). Batteries are energy storage devices. Other energy storage options have different efficiency, e.g., the production of hydrogen through electrolysis of water (a fuel cell acting in reverse) is close to 80% efficiency [26].

Many modern energy conversion systems involve fuel reforming, e.g., the conversion of coal to synthetic gas (a combination of hydrogen and carbon monoxide) or the conversion of natural gas to hydrogen. The reforming efficiency of these process, measured as the chemical energy in the fuel produced divided by the chemical energy of the fuel used, ranges from 80% for NG to $H_2$ or coal to syngas ($H_2 + CO$), to lower for values coal to hydrogen. In renewable system, wind turbines have a maximum efficiency close to 60% (measured as the kinetic energy of rotation as a fraction of the wind kinetic energy), but actual turbines deliver efficiencies close to

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[19] The fuel chemical energy can be defined as the higher or the lower heating value, or the free chemical energy/chemical availability, depending on the system and conversion processes.

30–40%. Photovoltaic systems deliver 10–20% efficiency for the electric energy output divided by the solar energy input, but their maximum efficiency depends on the design, e.g. single bandgap vs. multi bandgap crystalline cells or amorphous thin films. Other important efficiencies include:

- The light energy output divided by electrical energy input for light bulbs, which ranges from 2 to 10% for incandescent to fluorescent light, respectively;
- Photosynthesis efficiency, which measures the chemical energy stored by the plant as a fraction of the incident sunlight, ranges between 1 and 2%, and is limited to close to 8%.

In all these efficiencies, the balance is another form of "useless" energy. Measures can be taken to change the overall utilization efficiency of a source if this "useless" energy is captured and utilized in another application, e.g., using combined heat and power (CHP) approaches, one can capture some of the exhaust thermal energy for heating purpose.

## 5. Low carbon fossil conversion technologies

An effort to address two of the major concerns raised in the review of the recent trends in energy utilization and its impact on the environment, that is: the depletion of fossil fuel resources and the rise in $CO_2$ concentration in the atmosphere with its alarming consequences, must consider a number of external factors. These include:

- The massive and expensive infrastructure employed for recovery, refinement, delivery, conversion and utilization of this fossil fuel based energy; and,
- The economic, social, political and security concerns.

Realistic strategies to address these concerns are likely to be based on gradual transition towards more efficient and less carbon intensive energy options. As shown in the discussion of the "wedges", multiple solutions that can be implemented in parallel are necessary in this effort, keeping in mind that solutions that suitable for developed countries may be different than those suitable for developing economies. Solutions that address the needs of remote and sparsely populated areas are different from those that work best in heavily populated or industrialized areas. Viable carbon dioxide reduction solutions depend strongly on:

- The cost of improved efficiency, which depends of the fuel price and the cost of improved conversion technology.
- The availability of different forms of fossil fuels, e.g., NG vs. coal, with significantly different carbon dioxide emissions characteristics;
- The available local sources of renewal energy, their cost and scalability;
- The public perception of nuclear energy safety and the development of solutions to some of the outstanding problems associated with long terms waste storage and proliferation.

Solutions will be driven by policies and economic incentives, which could change the balance between centralized power and distributed power hence by support the expansion of the use of renewable energy, and encourage the transition from fossil based to renewable or hybrid based energy systems.

Given these factors, a high priority solution is improving the efficiency of energy conversion and utilization. Here, conversion refers to the production of useful forms of energy, e.g., thermal, mechanical or electrical energy, from its original form, e.g., chemical energy. Utilization efficiency refers to how efficiently the final product is being used, e.g., insulation of heated spaces and reduction of aerodynamic and other forms of drag resistance in vehicles. Using thermodynamic terminology, efficiency related issues may be posed in the following question: *"do we have an energy crisis or an entropy crisis?"* In other words, are we utilizing the source availability as well as we should, or are we wasting a good fraction of it during conversion or while it is being used to perform certain functions. Improving efficiency on both conversion and utilization fronts prolongs the lifetime of available fuels and reduces their environmental impact. We should note that improvements in efficiency are likely to come at the expense of paying more for the systems that convert or utilize more of the available energy of a given source. The added expense and can only be offset be charging higher fuel prices, providing other monetary incentives for energy efficiency, or relying on cultural and social attitudes that favors reducing our environmental footprint.

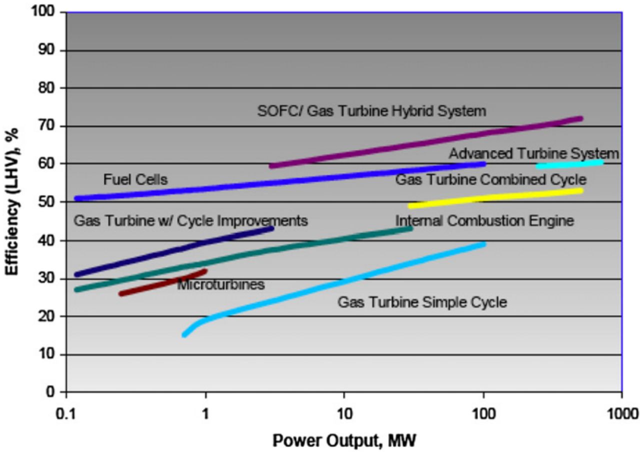

**Fig. 22.** The efficiency of several chemical to mechanical energy conversion systems and its scaling with the power (FC Handbook, DOE [27]). The focus of the diagram is electric power generation. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

In the discussion of the "wedges", doubling the efficiency of power plants and doubling vehicle mileage were suggested. Neither of these scenarios is out of reach, and Fig. 22 shows the efficiency of a number of power systems, which are currently in use or are under development for electricity generation [27]. The figure shows the efficiency gain as the scales grow, favoring centralized production of electricity. Note that the power output is shown in logarithmic scale, and maximum efficiency is reached when the plant is scaled up to several hundred MWe plants. These data demonstrates the advantages of adopting more advanced systems, e.g., combined cycles or hybrid fuel cell thermal cycles, in large-scale plants. This, however, might work against combined heat and power (CHP) plant applications, which maximize the utilization of the thermal energy of the fuel by splitting it between electricity production and the use of exhaust thermal energy for heating purposes. These CHP plants must be built close to where the thermal energy is being utilized, and hence favor the concept of distributed power. Efficiencies shown in the figures are for "simple" fuels such as natural gas or refined liquid fuels. Fuels that require extensive processing and exhaust gas clean up, such as coal, achieve lower overall efficiencies. For instance coal power plants employing supercritical and ultra supercritical cycle reach 45% efficiency. High-temperature fuel cells, such as solid oxide fuel cells show efficiencies close to 50% (which depends on the power density as well) and when hybridized with gas turbine or combined gas–steam cycles, can exceed 60%.

The lifetime of fossil fuel power plants is long, often exceeding 50 years, and hence their impact is enormous. Improving their conversion efficiency should have a strong near-term impact, and investing in such improvement seems wise. Being stationary, it is possible to consider efficient means of capturing and sequestering $CO_2$ in these stationary plants, hence making them near zero $CO_2$ emission. As will be shown, capture and sequestering carbon dioxide is energy intensive, and is only sensible if the original plant's efficiency (without capture) has been maximized.

### 5.1. Chemical energy

The conversion of chemical energy to mechanical or electrical energy is a rich field that offers significant opportunities for efficiency improvement and, with sufficient modification over the current practice, for carbon capture and sequestration [28]. Electricity generation in the U.S. is currently the largest carbon dioxide emitter because of the extensive use of coal, a trend that is likely to continue given the availability of the fuel and its low price. Developing countries such as China and India are rich in coal resources and are likely to exploit their natural resources to meet their growing energy needs. While the efficiency of coal plants has been rising because of the implementation of supercritical and ultra supercritical cycles, and regulated emissions from these plants, such as $NO_x$, $SO_x$ and particulates, have been reduced significantly, $CO_2$ emission per unit energy production from coal plants is highest among all fuels. Capture of carbon dioxide from coal and other fossil fuel powered plants for the purpose of storage/sequestration, use in enhanced oil and gas recovery, and other industrial processes is an attractive option for reducing $CO_2$ emission if geological storage proves to be successful [29].

The use of natural gas in electricity production has expanded significantly over the past two decades. Natural gas fueled power plants have significant advantages because:

- They have higher efficiency; natural gas can easily be used in combined gas–steam cycles that reach efficiency close to 60%.
- Natural gas is easy to transport in pipelines.
- It produces less carbon dioxide per unit chemical energy due to its higher hydrogen content and higher conversion efficiency.
- Natural gas is a clean burning fuel, producing lower NO and CO and negligible $SO_x$ and particulates that other fuels.
- Because it is a clean burning fuel, it is possible to build smaller plants in urban areas and hence reduce transmission losses.
- It is also possible to use natural gas in combined heat and power (CHP) production, a much more efficient alternative to centralized often remote power plants.

For this and other reasons to be discussed later, some consider natural gas as an ideal "alternative" fuel. However, natural gas resources are much more localized worldwide and, overall, represent a smaller fraction of the total available fossil fuels.

Power plants that can reach 60–70% overall efficiency, measured as the electric energy output as a percentage of the fuel's lower heating value, have been proposed. These plants incorporate tightly integrated, high efficiency components consisting of some of the following combination:

- Thermochemical components for reforming, gasification and combustion;
- Thermomechanical components such gas and steam turbines for the production of mechanical energy;
- Electrochemical components such as high-temperature fuel cells for the direct conversion of chemical energy to electricity; and,
- Possibly thermoelectric elements capable of converting low quality heat to electricity for waste heat recovery.

The large-scale deployment of these plants poses several challenges, including the development of high efficiency components, the integration of these components, and the environmental control technology. If equipped to capture carbon dioxide, the efficiency will be lower, as will be shown later, and the technology needed to separate $CO_2$ from the exhaust stream and store it will also have to become available and economical. It is currently possible to reach 55% efficiency in natural gas combined cycle plants, without $CO_2$ capture and without the need for fuel cells. Advanced power plants employ advanced high temperature gas turbines with inlet temperature close to 1400 C, integrated with supercritical steam cycle steam pressure exceeding 250 bar and 550 C. Practical efficiencies using natural gas are getting close to their thermodynamic limits.

Beyond natural gas, fuel flexibility is important to enable the use of low-grade fuels such as coal, refuse oils, refinery byproducts such as petcoke, biomass sources including agricultural and animal byproducts, etc. while keeping the emissions low and efficiency high [30]. Fig. 23 shows the component layout of a plant that uses gasification to enable the utilization of a range of solid and liquid fuels, while incorporating high-temperature fuel cells, gas turbines and steam turbines to maximize the overall conversion efficiency (total electric energy output as a fraction of the input fuel chemical energy). Using a gasifier, a mixture of coal (or other liquid and solid fuels), water and oxygen is converted into a mixture of carbon monoxide and hydrogen, and other gases (and solids if the fuel is contaminated with noncombustible residues). The "syngas" is cleaned up to remove acidic and other undesirable gaseous compounds and solid residues, and is then used in the fuel cell to generate electricity at high efficiency. To avoid poisoning the fuel cells or damaging the gas turbine, the syngas must be free of sulfuric compounds, ashes and other metallic components. The high-temperature fuel cell exhaust is used directly, or after combusting the residual fuels, in a gas turbine. The hot exhaust of the gas turbine raises steam for the steam cycle. While using coal as a fuel, and because of the expected high conversion efficiency of the fuel cell, predicted efficiencies for these cycles are in the range of 50%. Existing integrated gasification combined cycle plants that do not incorporate a fuel cell have efficiencies lower than 45%. It is possible to use direct coal combustion–steam cycle plants and reach 45% efficiency if supercritical cycles are used. However, gasification based plant produce less regulated pollutants such as sulfur oxide, nitric oxides and particulate matter, and they are more carbon dioxide capture compatible. On the other hand, they are more expensive and more complex to operate [31].

### 5.2. $CO_2$ capture approaches

Reduction of carbon dioxide emissions from power plants burning hydrocarbons by separating and storing $CO_2$ has been the subject of extensive research recently, and several schemes have been proposed. One overriding factor in the design of $CO_2$ capture enabled power plants is to maximize the plant efficiency by using combined gas and steam cycles and, in the future, hybridize these mechanical components with fuel cells. Maximizing the plant efficiency counters the efficiency penalty associated with carbon dioxide separation (or other gas separation processes incorporated for the same goal, such as air separation in some designs). It is important to maximize $CO_2$ concentration in the stream before separation to minimize separation energy penalty. As shown in Fig. 24, low carbon energy conversion schemes for power production include

- Post-combustion capture;
- Precombustion capture;
- Oxyfuel combustion; and,
- Electrochemical separation.

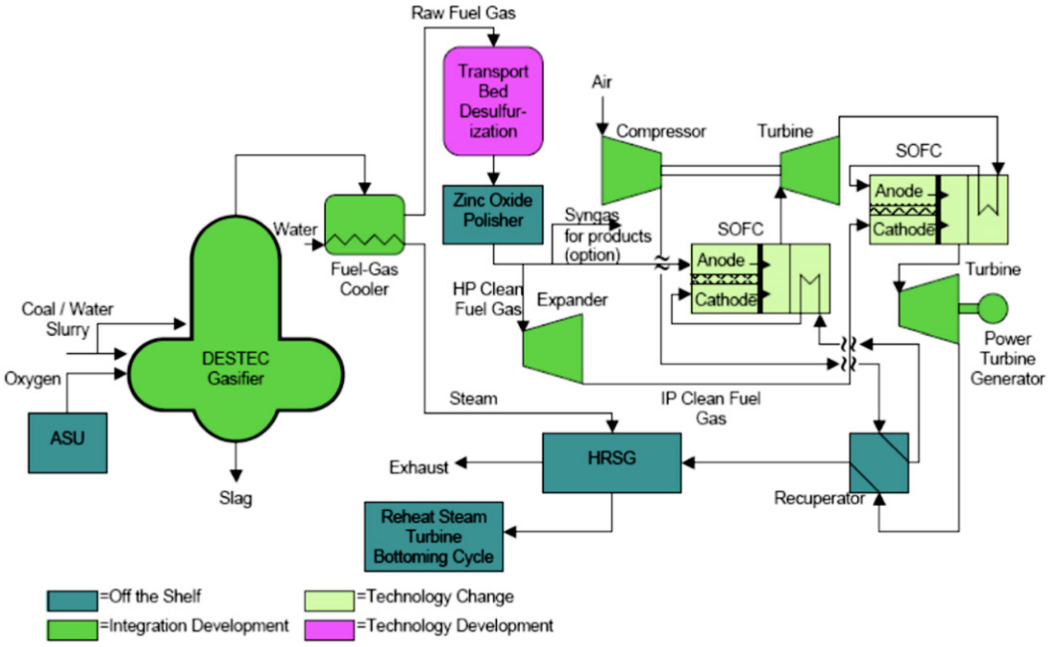

**Fig. 23.** Layout of an integrated gasification combined cycle power plant, in which the conventional gas turbine-steam turbine combined cycle is equipped with a "topping" high-temperature fuel cells to maximize the overall conversion efficiency [27]. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

The first option is the simplest to implement, and requires the least modification of the power cycle, while the last is the least technologically developed. The first approach is most suitable for retrofit of existing power plants since it requires least modification of the power plant itself. However, it is not necessarily the most efficient low-C plant layout, and that motivates investigating other options. The second and third options may require some special equipment, such as $CO_2$ gas turbine for oxyfuel combustion and $H_2$ turbine for precombustion separation of carbon dioxide. In the case of coal, precombustion separation requires gasification in an integrated gasification combined cycle (IGCC) plant, shown previously. The last option relies on the development of robust and efficient fuel cells for high-temperature operation, that are also affordable. In general the efficiency penalty of $CO_2$ capture depends on the fuel, and the optimal design may not be the same for coal and NG. Note that in gasification based coal power plants, $H_2S$ is captured from the flue gases before these gases are used in a gas turbine or a fuel cell (or before they are emitted in the exhaust gases since sulfur compounds are heavily regulated). It is possible that the total acid gas ($CO_2$ + $H_2S$) can be removed in the same step (instead of removing the two components separately), thus improving the economics of the capture strategy.

### *5.2.1. Post-combustion capture*

As mentioned before, the simplest carbon dioxide capture strategy is the post-combustion capture option, in which carbon dioxide is removed from the flue gases using chemical scrubbing techniques, as shown in Fig. 25. Depending on the fuel used, $CO_2$ concentration in the products can be as low as 3% for lean burning NG and much higher for coal plants, with precise values depending

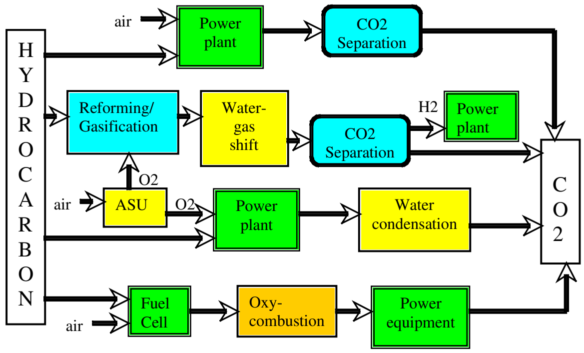

**Fig. 24.** Different approaches to carbon dioxide capture from power plants, including post-combustion capture, oxyfuel combustion and precombustion capture. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

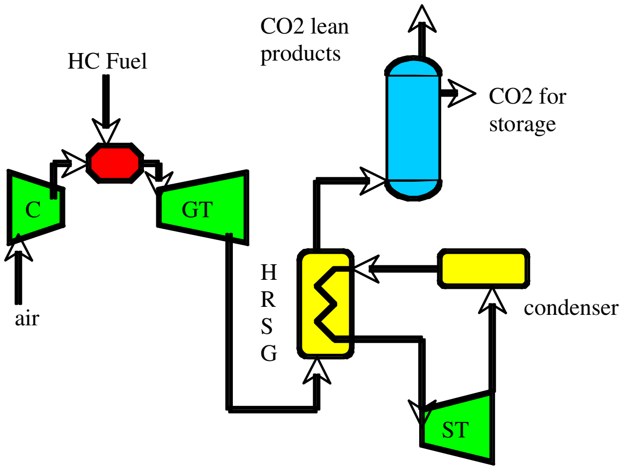

**Fig. 25.** Schematic layout (overly simplified for illustration) for a post-combustion decarbonization process in which separation of $CO_2$ from flue gases using chemical absorption is shown. Compressed NG, or coal-produced synthetic gas is used as a fuel. HRSG stands for the heat recovery steam generator necessary for the high efficiency combined cycle. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

on the combustion stoichiometry and plant design. Gas separation processes are energy intensive, and their integration into the power generation cycle lowers its overall efficiency.

Chemical separation processes utilize a solvent to remove $CO_2$ from the exhaust gas stream of a conventional power plant. This is performed in the absorbent tower. Next, thermal energy is needed to regenerate the solvent, i.e., separate carbon dioxide from the solvent for reuse. For instance using monoethanolamine (or other amines) as an adsorbent dissolved in an aqueous solvent requires thermal energy to regenerate the absorbent before it can be recycled back to the absorption tower. This thermal energy can be provided by steam extracted from the low-pressure stages of the steam turbine. More energy is required for pumping the solvent in the absorption plant, and for compressing and liquefying the carbon dioxide. It has been estimated that $CO_2$ capture from coal plants using post-combustion capture would reduce their efficiency by 8–16 percentage points depending on the plant type, flue gases, the absorbent used and its percentage concentration in the solvent, and the integration of the plant. In natural gas combined cycle (NGCC), that efficiency loss is estimated to be less, 5–10 percentage points. The lower range of losses is achieved by recycling some of the exhaust gas back to the combustor while burning a stoichiometric mixture, that is, by using a higher $CO_2$ concentration in the working fluid since raising the carbon dioxide concentration at the separation point reduces the specific separation energy. Carbon dioxide compression and/or liquefaction for transport and storage add 2–4 more percentage points of efficiency loss. Ongoing research on different absorbents and other advanced separation techniques may reduce the minimum efficiency penalty in these plants. We note here that the ideal separation work, expressed in terms of fuel chemical energy, i.e. the efficiency penalty is 2–3 percentage points. Therefore, there is significant room to improve $CO_2$ separation technology and design low C conversion plants. Given current efficiencies of coal and NG plants, the efficiency reduction amounts to increasing the fuel consumption by 24–40% and 10–22%, respectively, to produce the same electrical energy output.

### 5.2.2. *Oxy-fuel combustion*

In oxy-combustion schemes, an air separation unit is used to produce the pure oxygen needed in the fuel combustion process, as shown in Fig. 26. The products of this combustion, which constitute the working fluid for the power machinery, are water and carbon dioxide (after removing contaminants in case of coal). Following the power machinery, water can be condensed and carbon dioxide captured directly, without expending extra energy. The efficiency penalty in this case is related to the energy required for separating oxygen from air, and small amount for recycling some $CO_2$ back to the combustor to moderate the combustion temperature. Large-scale distillation units are used for air separation, and for smaller plants, membrane based separation units can be used. Oxy-fuel combustion reach temperatures that are too high for gas turbine applications, and hence a large fraction of $CO_2$ must be recycled as a thermal mass to keep the temperature moderate enough in the combustion process.

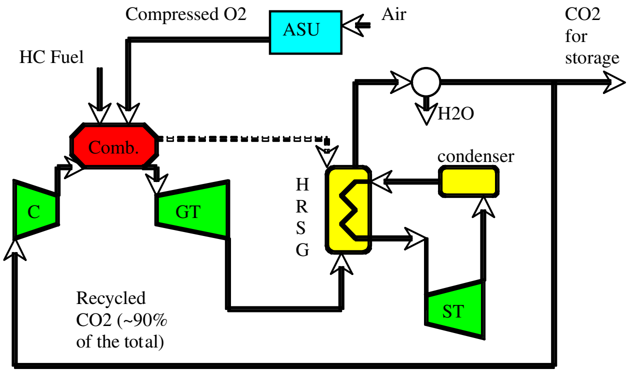

**Fig. 26.** Schematic layout (overly simplified for illustration) for an oxyfuel combustion process, in which an air separation unit is used to deliver oxygen to the gas turbine combustion chamber [9] the fuel here is either NG or syngas. Broken line is for pulverized coal combustion. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

Here also a combined cycle power plant is used to maximize the plant efficiency and to make up for the energy penalty incurred in the (indirect) $CO_2$ capture process. Studies show that natural gas fired cycles based on this concept can reach 40–50% efficiency with $CO_2$ capture. The net efficiency depends on the maximum cycle temperature and pressure, the detail of the heat transfer processes in the regenerators and/or HRSG, and the working fluid. It is also possible to apply this concept to coal fired cycle. For instance, recycled carbon dioxide can be used in the coal boiler to reduce the combustion temperature, while capturing a fraction of $CO_2$ following the heat transfer to the steam cycle. Estimates for efficiency penalty in this case are 5–7 percentage points for the air separation unit (ASU) and 4 percentage points due to the recycling of carbon dioxide. Values for a net efficiency of 28–34% for optimized steam cycles with oxy-combustion have been reported (without the $CO_2$ liquefaction energy). The estimated reduction in efficiency for coal (synthetic gas) and NG are 5–12 percentage points and 6–9 percentage points, respectively. Given current efficiencies of coal and NG plants, this amounts to increasing the fuel use by 24–27% and 22–28%, respectively.

More recently, tightly integrated combined-like cycles have been proposed in which oxy-combustion is used, with large fractions of the working fluid, which includes high percentages of $CO_2$, being recycled. In some of these cycle designs, higher-pressure wet carbon dioxide working fluid replaces typical combustion products. One example of this cycle is the Graz cycle shown in Fig. 27 [32]. Depending on the maximum pressure and temperature of the cycle, efficiencies higher than 50%, with $CO_2$ capture, have been estimated. Other examples include the MATIANT cycle [33]. Other cycles that rely on chemical recuperation and chemical looping have also been suggested.

### 5.2.3. *Precombustion capture*

The third approach, precombustion capture, involves partial oxidation of the hydrocarbons fuel, in the form of reforming (for natural gas) or gasification (for coal) of the fuel, to syngas ($CO + H_2$) in pure oxygen (or in air, especially in the NG case), see Fig. 28. Partial oxidation is followed by a gas-water shift reaction to oxidize the carbon monoxide to carbon dioxide and increase the hydrogen content of the stream. Carbon dioxide is then separated and pure hydrogen (and nitrogen if air is used in NG reforming) is burned in air in the combustion chamber of the gas turbine. The rest of the cycle is the same as other combined cycles. This approach reduces the load on the air separation unit since oxygen is required only for the partial oxidation of the fuel (in case when oxygen is used in the partial oxidation), and overall lower efficiency penalty than the previous two approaches has been predicted. Moreover, gas clean up in the case of coal is performed on smaller volumes (partially oxidized products), thus reducing the energy consumption and equipment size required for gas purification. Because of the large difference in molecular weight between hydrogen and $CO_2$, gas separation can be performed using different technologies, including membranes, but physical absorption or adsorption can be used as well, especially when high-pressure gasification or reforming is used. Since the gas turbine fuel is pure hydrogen,

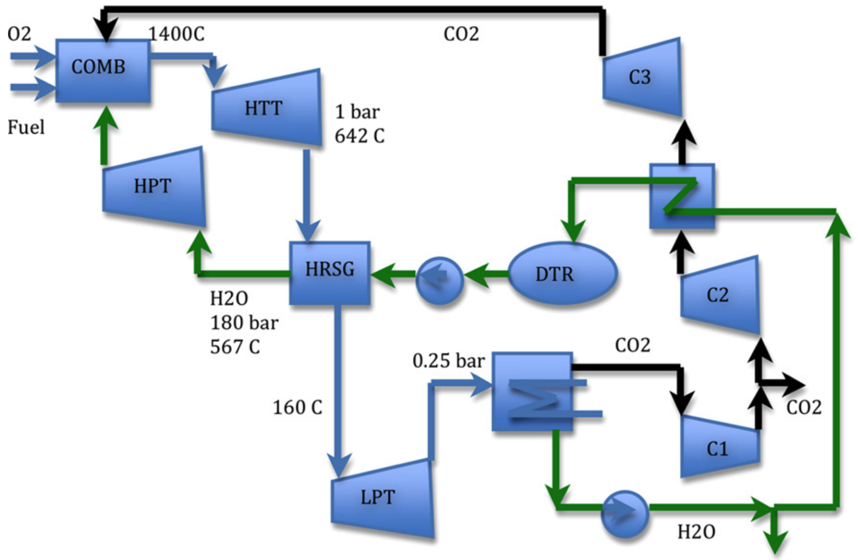

**Fig. 27.** The Graz cycle uses oxyfuel combustion in recirculated $CO_2$, HTT: high-temperature turbine, LPT: low-pressure turbine, HPT: High-pressure turbine, C1–C3: $CO_2$ compressors [32]. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

either lean combustion is used or the nitrogen separated from the air in the ASU is reintroduced into the gas turbine combustor to lower the temperature. Special gas turbines that tolerate high moisture content in the working fluid are under development. The estimated reduction in efficiency for coal (syngas) and NG are 7–13 percentage points and 4–11 percentage points, respectively. Given current efficiencies of coal and NG plants, this amounts to increasing the fuel use by 14–25% and 16–28%, respectively [34].

### *5.2.4. Electrochemical separation*

It is possible to use a high-temperature fuel cell to convert the chemical energy in fuels directly to electricity, especially in case natural gas or coal-produced syngas are used as fuels. High-temperature fuel cells can achieve high efficiency, especially when used in the low current/low power density mode. Moreover, they produce a products' stream of $CO_2 + H_2O$, at the exit side of the fuel channel (the anode side). This is done without the need for an air separation unit, and air separation occurs electrochemically, on the cathode side. The fuel gas is introduced on the anode side, and is electrochemically oxidized by the oxygen ions that migrate across the solid electrolyte (ion transport membrane) from the cathode side to the anode side, as shown in Fig. 29. On the anode side, carbon dioxide and water form as products, without being contaminated with nitrogen, which stays on the cathode side. If all the fuel is used on the anode side, there is no need for further gas separation system; only water condensation is necessary to produce pure $CO_2$. Otherwise, the leftover fuel in the fuel cell exhaust stream can be burned in oxygen to power a gas turbine or a combined cycle power plant (bottoming cycle for the fuel cell).

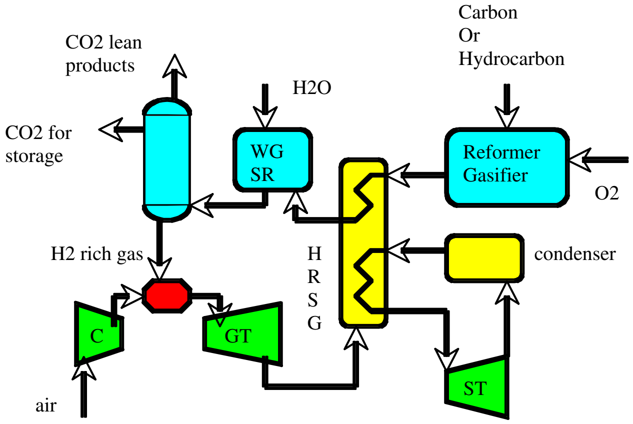

**Fig. 28.** Schematic layout (overly simplified for illustration) for precombustion power generation process, syngas is produced in either in the NGR, the natural gas reformer, or in a coal gasifier. Next, the syngas is cooled (with heat going to the heat recovery steam generator), and the cooled gas (the fat arrow is for heat transfer) is introduced into the water-gas shift reactor (WGSR) to convert CO–$CO_2$ using steam. Following this step, $CO_2$ separated from hydrogen and the latter is burned in air. An air separation unit is still needed for oxygen. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

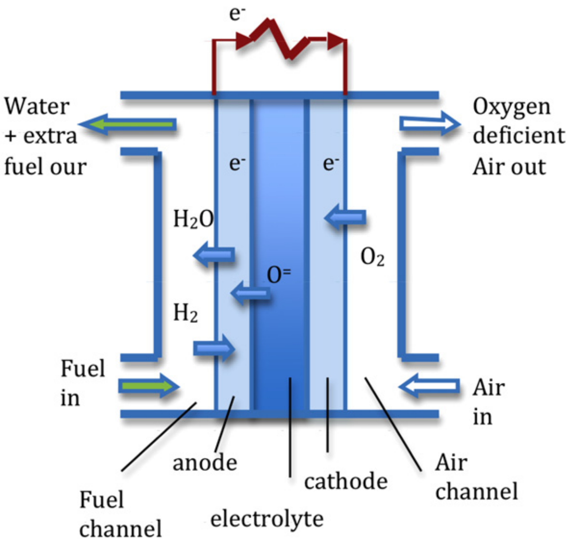

**Fig. 29.** The electrode membrane assembly in a solid oxide fuel cell. Oxygen is introduced at the cathode side, where it reacts with electrons to form ions that migrate across the solid electrolyte. On the anode side, these ions react with the fuels electrochemically to oxidize the fuel forming water and carbon dioxide and electrons. The products of combustion are essentially $CO_2$ and $H_2O$. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

Thus, using a high-temperature fuel cell reduces substantially the need for an ASU, although some more pure oxygen might be necessary to burn the residual fuels from the fuel cell. This electrochemical separation approach requires the least separation energy and hence achieves the highest overall conversion efficiency with $CO_2$ capture. The estimated efficiency penalty is 6 percentage points. SOFC technology is under development. Solid oxide fuel cells for large-scale electricity production applications are still under development, especially those using hydrocarbon fuels.

Depending on the capture strategy, and except for separation from flue gases using currently available chemical absorption technology, the "decarbonization" power cycles described in this section need some special equipment especially on the power island side, such as wet carbon dioxide gas turbines that operate at high pressure and temperature, gas turbines that use pure hydrogen as a fuel. Such equipment is currently under development or under consideration. Furthermore, gas separation technologies compatible with low $CO_2$ concentration are required. For separation from the flue gases, amine-based chemical scrubbing is most suitable because of the low concentration of $CO_2$ in flue gases. For precombustion capture approaches, physical separation using pressure swing absorption is most compatible with the higher pressures of the gas stream containing carbon dioxide. Membrane separation that takes advantage of the difference between the molecular weights of hydrogen and carbon dioxide has also been suggested, and is likely to become available for large-scale applications in the near future [35]. More advanced concepts, such as chemical looping for gasification and $CO_2$ capture without the use of a separate gasifier and air separation units, have been proposed [36].

### 5.3. Synthetic fuel production

Decarbonization[20] concepts can be applied to synthetic fuel production plants, including those designed to produce hydrogen or other hydrocarbon fuels from coal or other heavy hydrocarbon sources, and for plants that might be used to generate electricity and synthetic fuel, or synfuel, from the same feedstock, simultaneously or on demand. The operation of these polygeneration plants can be optimized to maximize conversion efficiency and to deliver different products as needed. Precombustion capture lends itself well to this application, since many synthetic fuel production processes, e.g., so-called indirect approaches, start with the production of synthetic gas using traditional gasification of heavier hydrocarbons in oxygen and steam, similar to those shown schematically in Fig. 30 [37]. Following the cleanup of the synthetic gas, catalytic processes are used to combine the components of the gas at different ratio to produce hydrocarbons. Depending on the gasification medium and the follow-up reactions, e.g., water-gas shift reaction to change the $CO/H_2$ ratio in the syngas, carbon monoxide and carbon dioxide form at different concentrations, with higher $CO_2$ ratios attained when higher concentration of hydrogen in the syngas is desirable. Part of or all the $CO_2$ can be separated from the reformed synthetic gas stream for storage. As mentioned before in the discussion of power cycles, high-pressure gasification is preferred in part to reduce equipment size. Higher pressure lends itself to physical adsorption for $H_2$ separation from the shifted gas. If the plant is used for $H_2$ production, all carbon dioxide can be separated at this stage. Otherwise, only some would be separated following gasification, and CO would be used in Fisher-Tropsch fuel synthesis process. With $CO_2$ capture, and depending on the level of plant integration (heat and mass integration), the efficiency of hydrogen or other hydrocarbons production drops.

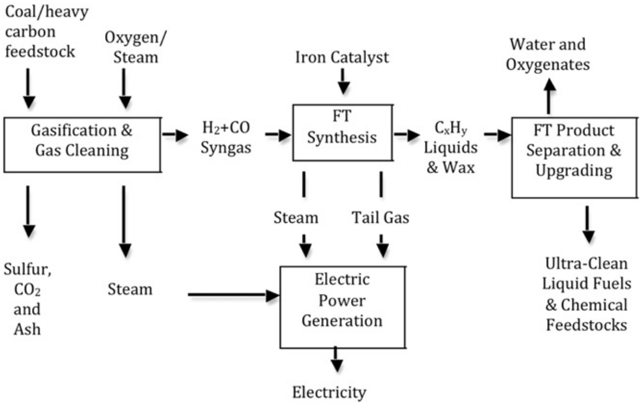

**Fig. 30.** An example of indirect liquefaction of heavy hydrocarbon using gasification, with partial separation of carbon dioxide, and production of liquid fuels from the clean syngas using Fischer-Tropsch (FT) synthesis (see [37]). "Tail gas" off the FT process are used in electricity generation, that is, the design allows for polygeneration.

Hydrogen can be produced by water electrolysis without $CO_2$ emission if the source of electricity is carbon free, or directly from high-temperature heat ($\sim$850 C) using thermochemical cycles. Nuclear energy is a scalable source of energy that can be used for both technologies. Water can also be reacted with carbon dioxide directly using high-temperature thermal energy in the presence of a catalyst to form synthetic hydrocarbons.

## 6. Zero-carbon technologies: nuclear and renewable sources

Zero-carbon energy sources are: nuclear energy; and, renewable sources, such as hydraulic, geothermal, wind, solar and biomass.[21]

Nuclear energy is a scalable source that can supply a reasonable fraction of future energy needs and can be easily integrated into the exiting electricity generation and distribution infrastructure. Concerns over waste management and storage; weapon proliferation and the public perception of safety should be addressed before substantial expansion of nuclear power plants can be expected. As shown next, hydraulic power, which contributes a significant fraction of renewable electricity, is near its peak, and has its own share of environmental problems. Other sources of renewable energy have much lower energy and power density than fossil and nuclear energy, and are characterized by high but varying degrees of intermittency.[22] Biomass is used extensively in rural communities in developing countries to provide thermal energy. More recently, efforts to produce liquid transportation fuels from certain biomass feedstock have intensified, but the potential of biomass energy is limited by land and water resources. The most significant renewable sources are wind and solar energy, and to some extend geothermal sources, but many technical and economic challenges remain.

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[20] "Decarbonization" and "Carbon Management" have become synonymous with the process of reducing the carbon dioxide that finds its way to the atmosphere.

[21] Other forms include ocean tidal waves and ocean thermal energy, which have not made much impact on the energy resources yet. All forms of renewable energy originate in solar energy, except for geothermal energy (original hot gases that formed the Earth) and ocean tidal waves (gravitational). It should be noted that the notion of zero-carbon power is relative, and for some forms, such as biomass, fossil fuels are still used in their production.

[22] Typically, fossil fuel power flows though components in power and propulsion applications is in the order of 100 $kW/m^2$, or larger for high-speed propulsion. Renewable source have energy-density flow rates 3–4 orders of magnitude lower, depending on the energy form. For instance, the average (total) solar power reaching the Earth's surface is, on average, O(300 $W/m^2$).

### 6.1. Nuclear energy

Nuclear energy currently provides 20% of the electricity needs of the United States, and more that 85% of that of France. Worldwide, it is estimated that nuclear energy supplies 6.4% of the primary energy (2.1% in the form of electricity), which amounts to near 17% of the electricity supplies. Nuclear energy has grown slowly because of the concerns over large-scale accidents, the problems of waste disposal and weapons proliferation. Nuclear electric power plants, totaling about 500 worldwide, use uranium 235, which is produced by enriching natural uranium. Light water reactors, both the pressurized and boiling water types, represent the majority of current nuclear reactors, but some plants use gas cooled graphite reactors. Progress has been made in designing passively safe reactors that reduce the chances of accidents, but current systems have yet to incorporate these designs at a large scale.

The ultimate limitation on fission energy, besides the waste disposal and security concerns, is thought to be the fuel supply. Current estimates for the ground-based reserves and ultimately recoverable resources of U-235 translate to 60–300 TW-year of primary power.[23] More uranium can be recovered from seawater, and large resources are known to exit thereon, but their extraction at large scales has not been attempted. Plutonium 239 is produced during the uranium reactions in power reactors, and can be separated from the spent fuel rods for use in sustained nuclear reaction for power generation, or for nuclear weapons. For this reason, reprocessing for spend fuels is currently banned in the US and most other countries. Fast breeder reactors, such as liquid metal cooled reactors can be used to produce plutonium 239 and another fissile isotopes, such as thorium 233.

Fusion has been considered as promising technology that does not produce radioactive waste and is less prone to accidents, but effort to achieve sustained power generation has evolved slowly, and remains extremely challenging. In fusion reactions, deuterium reacts with itself, with tritium or helium to form helium. Deuterium is abundant, and fusion reactions do not produce radioactive waste. However, producing more energy from fusion reactions than that consumed to initiate them has been very difficult. Demonstrating self-sustained electric energy production from self-sustaining fusion reactions is believed to be many decades and huge investments away. Efforts to use tokomak magnetic confinement of plasma to induce the fusion reaction, or high-powered strongly focused lasers to provide the energy for ignition, are underway. In contrast, fission-based nuclear energy remains as a scalable viable complement to fossil fuel energy and evolving renewable.

### 6.2. Renewable sources

A parallel strategy to efficiency improvement, CCS and nuclear energy, with intermediate to long-term impact should be based on expanding the use of renewable energy sources, including geothermal, wind, and solar energy and biomass sources. Accelerated deployment of renewable energy systems can be achieved by; (i) improving their conversion efficiency; (ii) reducing their cost; and, (iii) raising the monetary incentives for those who wish to adopt renewable energy. Improving energy storage systems, especially of those used to store electricity, is a requisite to large-scale introduction of solar and wind energy.

#### 6.2.1. Hydraulic power

Currently an important source of renewable energy is hydraulic power plants built at natural waterfalls or behind river dams. There is close to 0.7 TW capacity installed worldwide. Expansion possibilities are limited, the 18 GW Three-Gorges dam under construction in China being one of the last large-scale projects. Overall, hydropower, when nearly fully utilized, is not expected to exceed 0.9 TW. The capacity might decrease if climate change leads to different rainfall patterns. Hydropower is seasonable, but large dams reduce the oscillation in power production between seasons by creating high-capacity reservoirs that regulate the flow of water into the power plants. Moreover, contrary to other renewable sources, hydropower is not intermittent on day-to-day basis. However, hydropower is not without negative ecological impact, and large reservoirs of water created behind man-made dams can affect the local ecosystems. Downstream of a dam, soil can become less fertile as silt that used to replenish its nutrients is no longer able to flow. River fish population can also get negatively impacted, and some dams have been recommended for removal to revive fish habitats.

#### 6.2.2. Geothermal energy

A scalable renewable energy source is geothermal energy, which relies on drilling deep wells in areas where ground sources of hot fluids are available, and building thermal-electric conversion power plants that take advantage of the relatively small temperature difference between the source and the environment. The efficiency of these plants is relatively low because of the small temperature gradient between the hot and cold heat reservoirs. Organic Rankine cycles have been used to maximize the utilization of this small temperature difference. The potential capacity of geothermal energy is large, potentially reaching 10 TW worldwide. The current installed capacity is less than 10 GW electricity, and is limited by available and affordable well drilling technology. Most wells have a relatively small lifetime, 5 years on average, and new wells must be drilled to continue the plant operation. To reach its full potential, deeper wells, reaching down 5–10 km, will have to be used, and novel drilling technologies are under development for this purpose. Relatively newer concepts called “heat mining” or “Enhanced Geothermal Systems” that rely on drilling deep wells and fractioning the hot rock at the well bottom [38]. Fluids are then circulated between the power plant and the fractured rock to absorb the thermal energy and bring it up to the surface. Drilling deeper wells allows for higher temperature heat sources and hence higher efficiency, but is also more expensive.

Shallow sources of geothermal energy have also been used for distributed heating and cooling. Concepts for hybridizing geothermal energy with fossil fuels or with solar energy are being considered to improve the plant overall efficiency and extend its lifetime.

#### 6.2.3. Wind energy

Although wind and solar contribution to total energy production currently represent a very small fraction of the total supply, both have grown steadily over the past decade, in the range of 25–30%/year, and indications are that this trend will continue for some time. Fig. 31 shows the total wind capacity in the U.S., and the price of wind generated electricity over the past two decades. Notice that, like with other technologies, the price of the product, in this case electricity, falls rapidly at the early stages of technology improvement, and stabilizes as technology is adopted more widely. Part of the overall improvement in wind energy economics is associated with the design and installation of larger turbines, a trend that is expected to continue. Doubling the per turbine capacity is expected during the next decades, with further

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[23] If all current energy needs were to be met using nuclear fission energy using available uranium, these estimates would translate to 5–25 year supply [28].

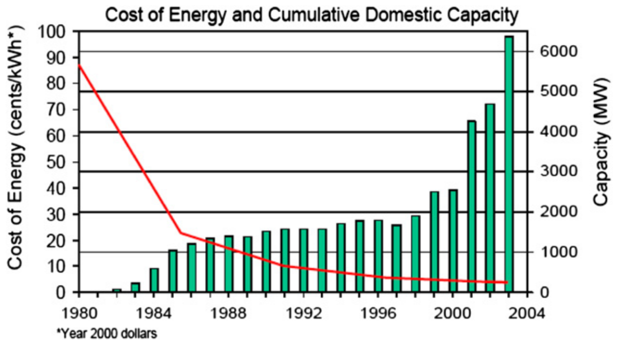

**Fig. 31.** The growth of the total installed wind energy capacity in the U.S. and the drop in price of wind generated electricity since 1980. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

innovations such as actively controlled blade pitch for variable wind speed and the installation of arrays of sensors and actuators to protect against wind gust and violent storms. Wind turbines with 5 MW capacity, at heights exceeding 120 m, have been proposed to harness wind speeds over a wider range of wind velocities. Larger size turbines are favored in off-shore installations, where the wind is stronger and less intermittent, and the impact on the local environment is minimized. The spread of off-shore technology will be enabled by progress in installation and maintenance technology. Current efforts to develop floating turbines, if successful, will be able to exploit the higher more sustained wind conditions deeper off-shore, while taking advantage of the experience in building and maintaining off-shore oil drilling platforms. Depending on the turbine size and the extent of the wind farm, wind energy technology offers solutions for remote, off-grid applications, distributed power applications and grid-connected central generation facilities. If located away from highly populated areas, wind turbine noise and visual impact can be minimized. Total potential wind capacity that can be utilized practically is believed to exceed 10 TW, including off-shore locations.

### 6.2.4. *Solar energy*

Expanding solar energy utilization is an important step towards meeting the rising energy demand while limiting $CO_2$ emissions. Solar thermal energy (heat) and solar thermal electric conversion for heat and power applications, respectively, are important for distributed utilization and centralized energy production [39]. The former has been used extensively for home heating and hot water production, while the latter is applied in central power plants. Progress towards integrating storage concepts into both applications is currently at the focus of the effort to overcome the intermittency of solar energy and for minimizing the need for fossil based back-up systems. In the solar thermal electric conversion, trough-based plants have been used successfully for more than two decades. Work is underway to scale this technology up to higher capacity using the power tower concept, as well as scaling it down using the solar dish concept. Trough collectors are 2D concentrators capable to delivering a relatively limited concentration ratio and hence relatively low heat-transfer fluid temperature, with optimum values around 400 C. Solar towers and solar dishes use 3D concentration technologies to achieve higher temperatures for the working fluid, between 600 and 800 C, and hence higher efficiency thermal conversion cycles. While a power tower is intended for large-scale applications, in the O(100 MW)[24] range and above, some have been build for smaller powers for demonstrating the concept, and to modularize the technology. Solar towers utilize heliostats, that is, a field of flat mirrors directed to reflect the light and concentrated it onto the top of the tower. The solar dish is intended for smaller more modular applications, O(20 kW), using a Stirling engines positioned at the focus of the collector. In this case, spherically shaped concentrators are used to concentrate solar radiation and raise the working fluid temperature further beyond what the trough can achieve, thus raising the thermodynamics efficiency of the cycle and simplifying the heat storage potential. While this technology has the advantage of not requiring a heat transfer medium between the collector and the power block, it requires a Stirling engine to operate efficiently given the relatively low-temperature heat source available. In the three cases, troughs, dishes and tower, tracking is necessary.

The power tower technology is currently undergoing significant expansion. Ground-based heliostats are used to focus the sun onto the tower top without the need to circulate a heat transfer fluid between the collectors. The smaller exposed heat exchange area reduces heat losses and improves the collection efficiency of towers. Built-in tracking mechanisms are important for maximizing the collection of solar energy throughout the day, and year. The large mirrors of the heliostat are spread over an area surrounding the tower; the area is proportional to the height and capacity of the tower. While large towers have been built, smaller modular towers have been proposed to simplify the construction and reduce the cost of deploying the technology at scale. Three dimensional concentration raises the temperature of the working fluid and hence the thermodynamic efficiency of the plant. The overall efficiency of power tower based concentrated solar power (CSP) is higher than trough-based CSP because of the lower heat losses from the collector and the higher conversion efficiency. The higher temperature of the heat transfer fluid reduces the size of thermal storage units as well.

Large-scale solar thermal electric applications rely on a two-phase power cycle to convert the collected and concentrated solar energy, the same power cycle used in steam power plants operating on coal or natural gas (or other external combustion systems). Hybrid solar-fossil operation can be beneficial in making the solar plant operable under cloudy conditions and at night, without the need for large-scale storage. The fact that the power island is already part of the solar plant makes the extra investment in hybridization small. In hybrid operation, the temperature of the working fluid is raised using a combination of solar and fossil energy, making it possible to use higher efficiency combined cycles. Hybridization can also be to retrofit existing fossil fuel power plants by installing solar collectors in their surrounding space, if available, thus making it possible for these plant to satisfy a fraction of renewable energy production. Fig. 32 shows a layout for such plant. Other developments for these SEGS (solar electric generation systems) include better tracking and higher efficiency collectors.

Table 3 summarizes the current state of the art of these three solar thermal electric technologies, as compiled by the US DOE. Large-scale solar power plants require large areas and are often built in a desert environment where solar radiation is strong. Given the energy density of solar heat, which averages about 150 W/m$^2$ (almost one half of the total electromagnetic energy), large areas must be covered with collectors to generate sufficient electricity.

Photovoltaic cells are convenient but expensive direct conversion devices that produce electricity from sunlight. Solar PV cells are solid-state devices, and hence require almost no maintenance. Semiconductors, such as silicon, when doped with small amounts of other elements can act as electron donors (n-type) or electron

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[24] O(xx) stands for order of magnitude of xx.

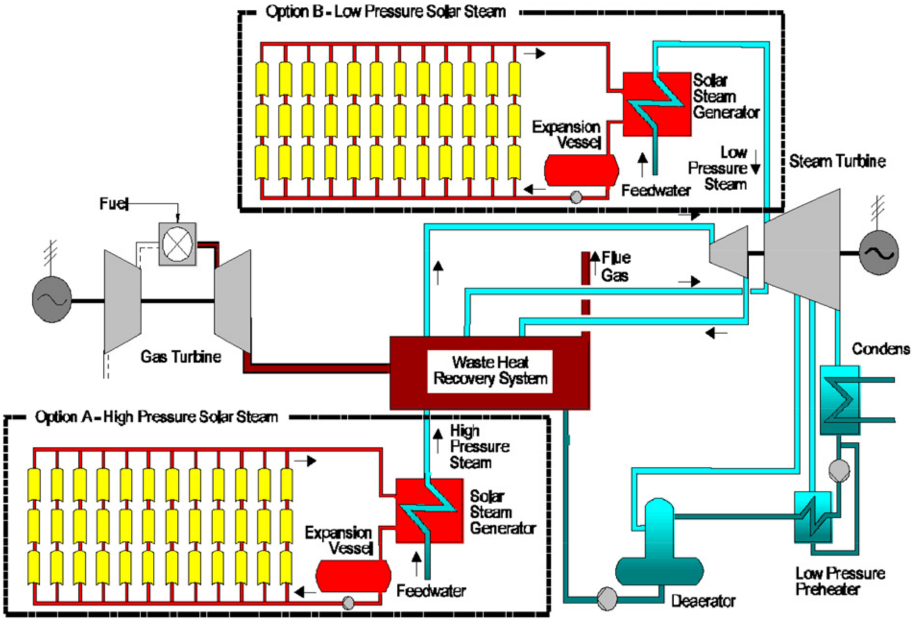

**Fig. 32.** Hybrid solar thermal- fossil fuel electricity generation power plant [39]. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

receptors (p-type). When two layers are joint, a potential difference is established when the cell is bombarded with photons of a particular wavelength (or energy exceeding the bandgap potential needed to move the electron from the valence band to the conduction band). The freed electrons move from the donor to the receptor in an external circuit. The efficiency of silicon type PV is 10–20%. Silicon based PVs have been used for small, distributed power applications, but their relatively expensive price of electricity (about 5X fossil based) has hampered their wide spread application for large-scale generation. Tax incentives are beginning to encourage adopting distributed solar power, and central generation is planned, Fig. 33 [40]. Recent development in nanostructured organic PV cells promise to lower their price and provide more flexibility in installation. Although these organic cells have lower efficiencies, they promise to be easier to fabricate, lighter in weight and more adaptable. Efficiency improvements are pursued by blending the polymers with electron acceptors, while optimizing the cell to promote efficient excitation splitting and charge transport by reducing the bandgap so that a larger fraction of the solar spectrum can be absorbed [41]. Grid-connected distributed PV applications could also become an attractive application for reducing the cost of installation, and tracking would be necessary to maximize power production. As in the case of wind, large-scale storage is necessary for reliable operation, especially in decentralized applications. Lack of storage limits the effort to take advantage of the vast solar potential.

More recently, approaches for the direct hydrogen generation from sunlight has been proposed (combined photovoltaic/electrolytic cells), and combined thermo and photoelectric conversion in the same hardware (Gratzel cell).

**Table 3**
Solar collectors available for solar thermal electric power plants, the operating characteristics of the plants using these collectors and cost estimates. Table taken from [39].

| | Parabolic trough | Power tower | Dish/engine |
|---|---|---|---|
| Size | 30–320 MW[a] | 10–200 MW[a] | 5–25 kW[a] |
| Operating temperature (°C/°F) | 390/734 | 565/1049 | 750/1382 |
| Annual capacity factor | 23–50%[a] | 20–77%[a] | 25% |
| Peak efficiency | 20%(d) | 23%(p) | 29.4%(d) |
| Net annual efficiency | 11(d')–16%[a] | 7(d')–20%[a] | 12–25%[a](p) |
| Commercial status | Commercially available | Scale-up demonstration | Prototype demonstration |
| Technology development risk | Low | Medium | High |
| Storage available | Limited | Yes | Battery |
| Hybrid designs | Yes | Yes | Yes |
| Cost | | | |
| $/m$^2$ | 630–275[a] | 475–200[a] | 3100–320[a] |
| $/W | 4.0–2.7[a] | 4.4–2.5[a] | 12.6–1.3[a] |
| $/W$_p$[b] | 4.0–1.3[a] | 2.4–0.9[a] | 12.6–1.1[a] |

[a] Values indicate changes over the 1997–2030 time frame.
[b] $/W$_p$ removes the effect of thermal storage (or hybridization for dish/engine). (p) = predicted; (d) = demonstrated; (d') = has been demonstrated, out years are predicted values.

### 6.2.5. *Biomass energy*

Biomass is the oldest and second largest source of renewable energy worldwide, following hydropower. Agricultural and silvicultural products and crops and their byproducts, as well as animal waste have been used as biosources (unused animal parts have also been used to produce fuels). Plants store energy through photosynthesis, converting radiation into chemical energy by combining carbon dioxide and water into carbohydrates, such as sugar, starch and cellulose, in photon-energized reactions. This energy can be converted back to other forms through combustion (as most biomass is currently used), gasification, fermentation or anaerobic digestion. During this process, or in follow-up conversion processes, $CO_2$ is released back, making biomass conversion carbon neutral as long as no fossil fuels are used in its production. While this may be the case is rural and developing economies, it is hardly the case in developed countries where some fossil fuels are usually used in agriculture, transportation and conversion of biomass. In case biomass is used to produce liquid fuels like ethanol for, e.g., transportation, it is important that the heating value of the fuel produced is larger than that of the fossil fuel used in the production process, that is the yield (output–input) is positive, or the chemical efficiency be larger than unity [42]. This is the case for high-energy crops, such as sugar cane, and when most of the crop residues are

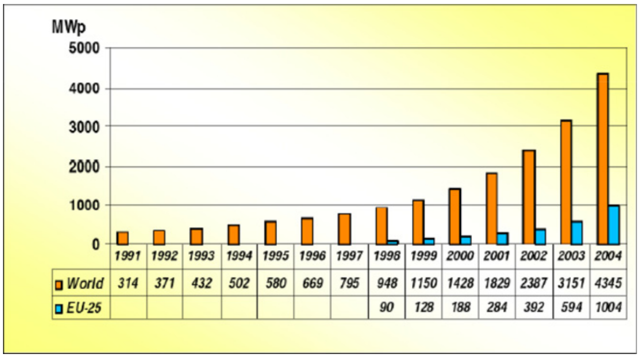

**Fig. 33.** Total photovoltaic installed capacity [40]. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

utilized in the fuel synthesis process. In the case of corn starch, estimates vary rather widely, and depend on the location of fermentation relative to production, and the processes involved in the conversion of starch to ethanol, as well as on the how the byproducts are valued. Besides, growing the crops, fermentation and distillation of ethanol are energy intensive, requiring the use of significant quantities of fossil fuels (currently mostly NG).[25] More recently, efforts have gone into producing organisms for the efficient conversion of cellulose, hemicellulose and lignin into ethanol, hence by increasing the yield beyond that attained from the grain alone. If successful and economical, this trend may enable the use of other lower value plant material in the production of biofuels.

Similar to hydropower, biomass is not devoid of negative environmental impact, such as the use of large quantities of water and fertilizers, insecticides and herbicides; soil erosion; and impact on the ecosystems such as deforestation. Some agricultural products are used to reintroduce some nutrients back into the soil and, if used in the production of biomass energy, will have to be replaced with synthetic fertilizers, or threaten weakening the soil. Moreover, growing crops for the production of biofuels utilizes land that would have been used for growing food crops, with potential negative impact on its economics and on the food supply. In general the scalability of biomass is limited, given the low photosynthesis efficiency. Photosynthesis has power density less than 1 $W/m^2$ (in thermal power units), which is more than an order of magnitude lower than that of wind and solar power density (in electrical energy), with the latter technologies producing electricity directly. However, biomass may contribute liquid fuels for transportation without the need for another storage medium. In the US, ethanol is currently being used as a fuel additive instead of the banned MBTE. Biodiesel, produced from soybeans and as a byproduct of cooking oils and some industrial processes, is another liquid biofuel.

## 7. Transportation

Transportation consumes 27% of the total energy utilized in the US, and produces a proportional fraction of $CO_2$ emissions. While these fractions vary from country to country, improved standards of living in populous countries are likely to make transportation a significant consumer of energy and produced of carbon dioxide emissions worldwide. The primary source of gasoline and diesel fuels, the most widely used transportation fuels, has been petroleum oil, although other hydrocarbons such as coal, tar sands and oil shale could be used to formulate similar fuels. Natural gas and propane have been also been used for ground transportation, and methane may find wider application in this sector in the future. When used to fuel internal combustion engines, natural gas enjoys similar advantage to those discussed in the context of electricity generation. With concerns over the depletion of oil resources, rising oil prices and tightening supplies, efforts are mounting to find alternative sources for transportation fuels. Chief among those are biofuels such as ethanol, a subject that has already been discussed early. While these alternative sources expand the availability of transportation fuel sources beyond petroleum, they do not address the carbon dioxide emissions issue. An exception to that is some biofuels produced from sugar products where some reduction of life-cycle $CO_2$ emissions is expected. Reduction of carbon dioxide emissions from the transportation sector is a significant challenge if vehicles remain reliant on an internal combustion engine optimized to run on gasoline or diesel. It is unlikely that onboard carbon-dioxide capture would ever be implemented, and $CO_2$ reduction from transportation vehicles will have to follow other strategies than those proposed for electricity generation. These alternative solutions are discussed next.

The most promising near-term solution for reduction of carbon dioxide emission from transportation vehicle is efficiency improvement achieved through more efficient engines and transmission, reducing the vehicle weight and improving its aerodynamics. From life-cycle perspective, improving both fuel production efficiency and transportation vehicle efficiency can also contribute to reducing transportation related $CO_2$ emissions. The use of low-carbon fuels such as natural gas and some forms of biofuels, the use of nuclear or renewable generated hydrogen to fuel internal combustion engines or fuel cells when they become available are other options for further carbon dioxide reduction. This may not be the case if hydrogen is produced by fossil fuel reforming without CCS, as discussed next. Transition to plug-in hybrid cars or pure electric cars, if the source of electricity is carbon free, is the ultimate zero emission modality.

It should be noted that fossil fuel produced hydrogen is unlikely to reduce $CO_2$ emission because of the inefficiencies in the fuel production process (near 60 or 80% when coal or NG is used, respectively), in the transportation of hydrogen from its production site to the distribution site, and during the charging and discharging of the onboard storage tank. All-electric vehicles, charged from high efficiency fossil electricity (grid electricity near 60% efficiency), nuclear or renewable electricity, are preferable when higher energy-density batteries becomes available. Besides engine efficiency, reduction of vehicle weight through the use of light material can have high pay-off in reducing fuel consumption and carbon dioxide emissions. Further gain in $CO_2$ reduction can be achieved if several of these improvements are done in parallel, and with the expansion of use of carpooling and public transportation, which themselves can be powered more by low C fuels, or electricity.

### 7.1. Drivetrain efficiency

The efficiency of internal combustion engines has been improving steadily over the years, and diesel engines have reached rather impressive values, see Fig. 22. While the trend is likely to continue, much higher engine efficiency is unlikely to be achievable, and transition to different powertrains along with improvements in aerodynamics and reduction in vehicle weight are necessary to gain substantial improvement in fuel economy. Efficient diesel engines already constitute a significant fraction of

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[25] Determining whether the yield is positive or negative requires complex calculations that start with the definition of the “system boundary”, that is, what is the input to the process or producing the fuel and whether, for instance, the chemical energy input to the production of the machinery used in agriculture should be included as input.

**Table 4**
Potential improvement in the fuel efficiency of internal combustion engine powered vehicle, the National Academy of Engineering, 2003.

| Technology | | Potential fuel efficiency improvement range (%) | |
|---|---|---|---|
| | | Low | High |
| *Engine technologies* | | | |
| Production-intent engine technologies | Engine friction and other mechanical/ hydrodynamic loss reduction | 1 | 5 |
| | Variable valve timing | 2 | 3 |
| | Cylinder deactivation | 3 | 6 |
| | Engine downsizing and supercharging | 5 | 7 |
| Emerging engine technologies | Camless valve actuation | 5 | 10 |
| | Variable compression ratio | 2 | 6 |
| | Intake valve throttling | 3 | 6 |
| *Transmission technologies* | | | |
| Production-intent transmission technologies | Continuously variable transmission CVT | 4 | 8 |
| Emerging transmission technologies | Automatic shift/manual transmission | 3 | 5 |

passenger vehicles and trucks in many parts of the world. In countries where this is not the case, like the US, the penetration of “clean” diesel into the passenger vehicle market can improve gas mileage given the inherent advantages of these engines. Clean diesel relays on advanced exhaust gas after treatment to reduce soot and $NO_x$ emissions using regenerative traps and catalytic urea based treatment, respectively. Engines that combine the advantages of gasoline engines and diesel engines, called homogeneous-charge-compression ignition (HCCI) or controlled ignition engines are under development that promise to achieve diesel engine efficiency with significantly less emissions.

Several studies have been conducted to assess the potential for significant improvements in the overall efficiency of internal combustion engine powered transportation vehicles. Table 4 summarizes the results of a study done by the National Academy of Engineering. Significant losses are encountered at idle and part load operation, especially in spark ignition engines. Several improvements are listed in the table, including changes in the engine and some in the transmission. Among them is variable valve timing (VVT) which can be used to change the fraction of exhaust gas trapping in the cylinders, which acts to control the power produced by the engine with reduced pumping loss while allowing partial lean burn and reducing throttling loss. Intake valve throttling at part load in multi valve engines leads to better charge motion and fast burn, while variable compression ratio makes it possible to increase efficiency at high power without the danger of knock. Cylinder deactivation has been used to control the power while avoiding pumping losses. Supercharging smaller engine is a promising trend because it increases the power density of the engine. Some of these improvements are already implemented in some production engines, including direct injection spark ignition engines. Other improvements listed in the table target the transmission technology as well as the reduction of friction and other hydrodynamic losses, which can have even more impact on the overall fuel utilization efficiency than improvements of the engine itself. Discussions of further improvement in the next paragraphs are based on a quantitative assessment of the origin of major losses.

A look at the losses during a typical driving cycle, shown in Fig. 34 [43], suggests ways to modify the drivetrain (or driveline D/L) to reduce fuel consumption. These modifications target how the engine is managed to reduce idle and part load losses, and how the power is sent to the wheels, but not the combustion engine itself. For instance, higher efficiencies can be achieved by shutting the engine down during idling and reducing the driveline or transmission losses. There are several implementations of these two options, but both can be accomplished by installing an optimized hybrid gas-electric powertrains. In this configuration, the combustion engine is mated with one or more electric motor, an electric generator and electricity storage devices. In this hybrid mode of operation, ideally the engine runs at or near its point of maximum efficiency most of the time, while the excess energy is stored when not needed. In case more power beyond what the engine can efficiently produce is needed, this power is drawn from a storage device. The elimination of idling loss by allowing the engine to shut off when not needed eliminates a significant source of losses, the so-called idle losses. Even higher overall efficiency in the hybrid powertrain is possible when regenerative breaking, which recovers and stores some of the breaking energy, is incorporated. Regenerative breaking requires a high power density storage device such as supercapacitors besides the batteries to absorb the break power. Minimizing the powertrain losses by better system integration between the different components is key to the success of these complex systems. Hybrids, however, must carry the extra weight of the motors, generators, and especially the batteries, which constitute a large overall weight penalty. The development of high energy and power density batteries is necessary for reducing the size and power of the internal combustion engine, and minimizing the number of starts and stops of the engine.

As shown in Fig. 35, a hybrid powertrain uses an engine to generate the necessary power, but utilizes the engine power in different ways depending on the design and how the power is transmitted to the wheel and shared by the storage device, typically a battery or a supercapacitor. In series hybrids, the wheels are driven by an electric motor, and the electricity for this

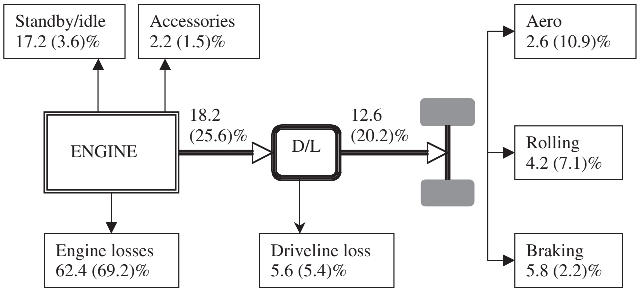

**Fig. 34.** Fractions of energy flow from the chemical source (the fuel) in the engine to other components as well as the losses experienced in an urban drive cycle a high way drive cycle (shown in brackets) [43].

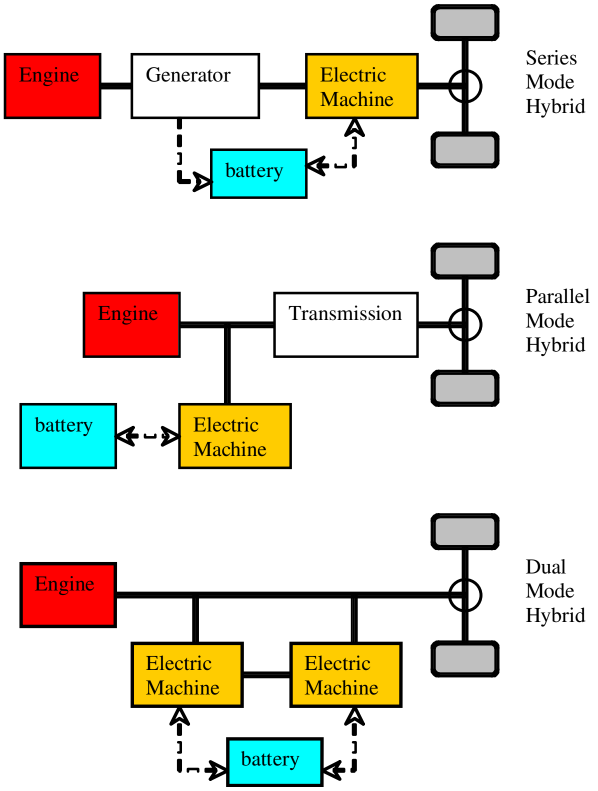

**Fig. 35.** Several hybrid drive train design using an engine, a generator, which is an electric machine that can act as a generator or a motor, and a transmission to drive the wheels. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

motor is supplied from a battery, or from a generator driven by a combustion engine, or from both the engine and the battery depending on the required power. This is a simple design that can run on the battery alone for short distances. However, the two-way conversion of the power during the charging and discharging the battery can result in significant losses. In the parallel hybrid, on the other hand, the wheels are driven by the engine, and in parallel by a motor when more power is needed. Electricity is supplied by the battery and the motor acts a generator when the engine power exceeds what is needed by the wheels. In this implementation, power can flow directly from the engine to the transmission, but the engine must always be running, at time at part load efficiency, and a transmission is required. The Honda Insight uses the parallel hybrid system. A third version is known as the dual mode hybrid, in which there are two motors, one drives the wheels directly and the other acts in parallel with the engine. Several combinations of the motor alone, or the engine and one or two motors can be used to drive the wheels depending on the power needs. This design takes advantage of the better features of both configurations, at the expense of more hardware complexity and an elaborate control system. This is the Toyota Prius system [44]. Hybrid vehicles use existing technology, but are capable of improving the overall conversion efficiency and can potentially achieve the maximum wheel-to-well efficiency.

Plug-in hybrids, equipped with larger and/or higher energy-density batteries that can power the vehicle for longer driving distances on electricity drawn from the grid are the next step for these hybrid systems. Grid electricity can be generated in high efficiency relatively low $CO_2$-NG power plants, $CO_2$-free nuclear power plants or renewable sources. Plug-in hybrids run primarily in the series-hybrid configuration, using a relatively small internal combustion engine to charge the batteries and to extend the vehicle range beyond the original grid-drawn charge. (A fuel cell can be used instead of the engine/generator to supply the electricity to the motor and the battery). With a sufficiently large battery, this configuration is favored for best overall carbon dioxide reduction in the hydrocarbon-based transportation system because of its overall higher efficiency and because it uses grid electricity that can be produced with lower $CO_2$ emissions, but without suffering the limitations of pure electric vehicles. Hybrid powered vehicles, which are starting to spread because of their compatibility with the existing fueling infrastructure, can be converted to plug-in hybrid mode by increasing the battery size and allowing for external charging. Plug-in hybrids are also considered by some as transition technology to fully electric transportation that require yet bigger and higher energy-density batteries. Clearly, significant improvements in hybrid and plug-in hybrid cars depend on higher energy-density electricity storage devices, both mass and volume based.

### 7.2. *Onboard storage*

Modern transportation vehicles use significant amount of electricity to power their computers, control systems, air conditioning, lighting and other functions and components. For some special purpose vehicle, electricity can be used for other functions as will, such as heating and powering cooling equipments. Generating this electricity directly using a high efficiency high-temperature fuel cell can reduce the load on the engine. A vehicle equipped with an auxiliary power unit (AUP) to generate electricity utilizes a smaller internal combustion engine. Moreover, the high-temperature fuel cell can run on the same fuel used to fuel the engine.

Transition from internal combustion engines to low-temperature proton exchange membrane (PEM) or similar fuel cells for transportation, which promises further increase in conversion efficiency beyond the internal combustion engine, idle elimination and zero pollution will require the development of efficient, large-scale hydrogen production, distribution and mobile storage technologies. Production of hydrogen as a transportation fuel, with low carbon dioxide emission, will require the transition from the current practice of producing hydrogen by methane-steam reforming without CCS to a similar practice but with CCS (using technologies described earlier). Steam reforming of coal is also possible, but with more $CO_2$ to be sequestered, as shown in Table 1. Alternatively, we will need to use nuclear electricity and electrolysis to produce hydrogen from water. Nuclear energy can also be used in the form of high-temperature heat to produce hydrogen by splitting water using one of several proposed thermochemical cycles. These thermochemical cycles, which might achieve overall higher conversion efficiency from thermal to chemical energy than currently possible from electrolysis (thermal to electrical to chemical), are still under development. Renewable electricity can be used to produce hydrogen by electrolysis as well. On top of the losses associated with the conversion of electricity to chemical energy stored in hydrogen, and the conversion of this chemical energy back to electricity to power the vehicle, other losses are incurred in the transportation, charging and storage of hydrogen. Direct use of renewable electricity is a more efficient option when long range electric cars become widely available.

Mobile storage of hydrogen is a complex challenge because of its extremely low volumetric energy density at STP, and relatively low volumetric energy density even at higher pressure or in liquid form. For mobile storage, high-pressure tanks can only be used for limited driving distances, and the requisite high strength material may add significantly to the weight of the vehicle. Cryogenic storage is energy intensive, using 40–100% of the energy that can be recovered from the stored hydrogen itself. Chemical storage of hydrogen in solid hydrides is a promising concept that is still underdevelopment. Another "chemical storage" option is to use liquid fuels, such as gasoline or diesel fuels, as a hydrogen carrier, and to produce hydrogen using onboard reforming. While reforming efficiency degrades the overall system's efficiency, many studies show a better overall efficiency using onboard reformed fuels than direct storage of pure hydrogen. This however produces a significant amount of $CO_2$ while driving.

### *7.3. Well-to-wheel efficiency*

Fig. 36 [45] shows a comparison between the overall, well-to-wheel efficiency of different transportation options, calculated as the product of the fuel production well-to-tank efficiency and the power plant tank-to-wheel efficiency. Many assumptions go into these calculations, and different results have been presented, but the overall trends have been demonstrated by other studies. Well-to-wheel efficiency, obtained using techniques similar to life-cycle analysis tools, is the overall efficiency of utilizing a source in transportation: it is the product of the fuel chain efficiency, also called well-to-tank efficiency, and the vehicle efficiency, or tank-to-wheel efficiency. The first includes the energy used in raw resource extraction, fuel production and transportation, and fueling the vehicles, all are combined to calculate the well-to-tank efficiency, that is the chemical energy in the fuel as a percentage of the chemical energy in the original raw material. The second component, that is tank to wheel, is essentially the vehicle fuel utilization efficiency. The two values vary widely depending on the fuel source and the drivetrain design. The study considered a range of fuel sources, fuels and engine and powertrain technologies.

Picking a clear winner from the well-to-wheel analysis is difficult given the assumptions used to obtain the numbers and the small differences between some options, but fuel cells using centralized production of hydrogen and diesel hybrid engines have some advantages, the former in the vehicle efficiency and the latter in the fuel chain efficiency. Diesel engines are currently available, but need to overcome some emissions problems, they are also more expensive that gasoline engines. As mentioned earlier, fuel cells are under development. Prices are not factored in this study. Several overall conclusions can be drawn form this figure. Natural gas improves the overall efficiency because it requires the least processing of all fuels, and as mentioned before, can improve the engine performance if the engine design takes advantage of the special combustion properties of natural gas. Fuel cells improve the overall efficiency because of their superior direct energy conversion efficiency. They remain, however, significantly more expensive than more conventional options. The efficiency of producing hydrogen is the lowest among other fuels, as stated previously. This low efficiency is however partially compensated by the higher tank-to-wheel efficiency. Nevertheless onboard hydrogen storage remains a serious impediment to its use in transportation.

A number of recent developments may help shape the transition strategy of personal transportation towards low $CO_2$ emissions, including the introduction of low sulfur diesel fuel in the US as well as ultra low emission diesel engines that incorporate advanced diesel exhaust clean up technologies. As shown in Fig. 36, diesel engines have superior well-to-wheel efficiency, and can exceed that of gasoline hybrid and of some fuel cell implementations, without the added cost of producing and diffusing these technologies rapidly and at a very large scale, and the associated infrastructure. Diesel engines are fully compatible with the existing fuel production and distribution infrastructure, vehicle design and production, and are fully scalable in size and power. Diesel fuels can be produced from different feedstocks, including biomass and recycled oils, heavier crude oils and gasified heavy hydrocarbons. Modern diesel engines, utilizing high-pressure injectors and turbocharging can achieve high power density and high efficiency. While benefiting less from hybridization than spark ignition engines, hybrid diesel engines can outperform hybrid gasoline engines as regards their efficiency.

In larger vehicles, such as buses and trucks, as well as some high mileage small personal transportation cars, compressed natural gas is being used more and more to replace traditional gasoline or

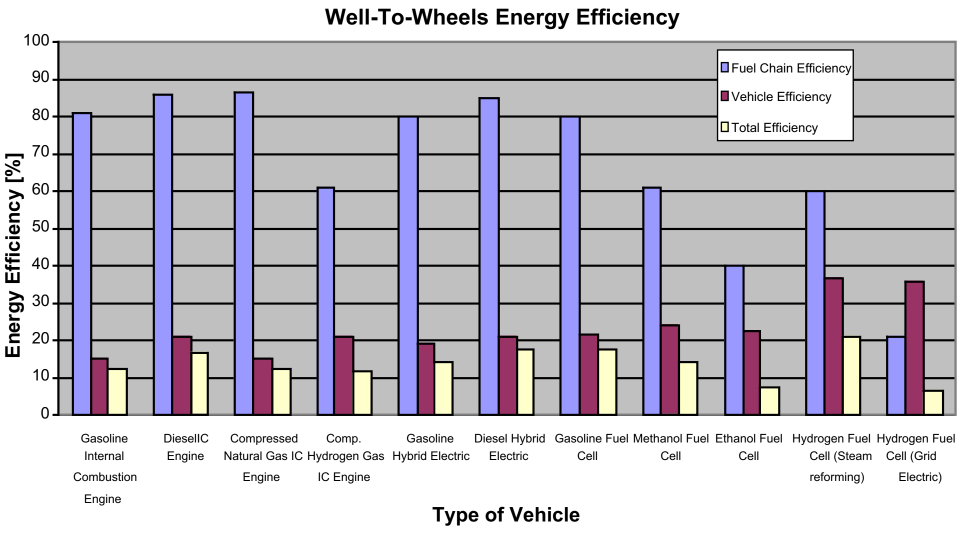

**Fig. 36.** Well-to-wheel efficiency of different power trains using different fuels. The total efficiency includes both vehicle operation and the energy required to produce the fuel. Extracting oil, refining gasoline and trucking the fuel to filling stations for IC engines is more efficient that creating $H_2$ for fuel cells. Source: Questions about a Hydrogen Economy. Wald, Matthew L., *Scientific American*, May 2004, Vol. 290, issue 5, page 66–73 (figure from page 70) [45]. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

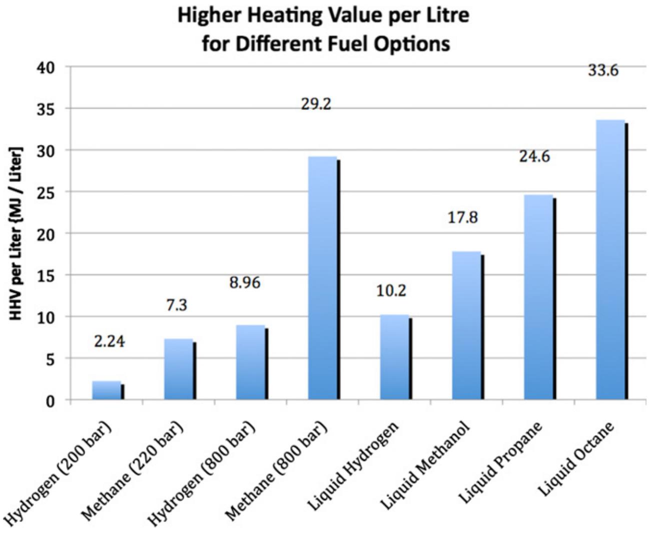

**Fig. 37.** The volumetric higher heating value per liter for a number of transportation fuels [46]. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

diesel fuels. Natural gas is easier to store because of its higher volumetric energy density, and it is a cleaner burning fuel than many other liquid fuels. Fig. 37 [46], shows the volumetric energy density of a number of transportation fuels under conditions of storage. While methane lacks behind liquid octane (shown as a surrogate to gasoline) even at extreme pressures, it outperforms hydrogen. Natural gas also produces the lowest amount of $CO_2$ per unit energy. Higher compression ratios can be used in natural gas spark ignition engines because of its higher octane number, and in compression ignition engines because of its higher ignition temperatures, further improving the engine efficiency. In some cases, mixing small amounts of hydrogen with methane (to form hythane) could further improve the combustion properties of methane and reduce carbon dioxide emissions further. Natural gas can also be used with onboard reforming to produce hydrogen for PEM fuel cells. In some crowded cities, natural gas is being used to replace diesel in public transportation to improve air quality, and in extreme cases, natural gas is being mandated for all form of ground transportation.[26]

As mentioned before, hybrid vehicles need high energy-density batteries to extend their range and benefit from hybridization. A hybrid car with no engine is simply an electric vehicle equipped with a large battery pack. Some promising trends in improving onboard electricity storage include the introduction of high performance lithium ion batteries into hybrid vehicles and electric cars. The energy density of these batteries is close to twice that of its near competitive, the nickel-metal hydride battery. However, as shown in Fig. 38 they are still about an order of magnitude lower than the corresponding values of combustion engines using gasoline or diesels. The comparison presented in the Ragone diagram shows the challenge to all-electric transportation; even when most advanced Li-ion batteries are considered, they still have substantially lower energy density that chemical engines (combustion engines or fuel cells). Other storage technologies that compete with these advanced batteries include supercapacitor and different flywheel designs, both having much higher charging and discharging power density compatible with regenerative braking at high speeds, and power surge during fast acceleration. Some hybrid configuration may use more than one storage device. The figure contracts the mass energy density of typical hydrocarbon fuels, and shows their vast advantage in energy storage.

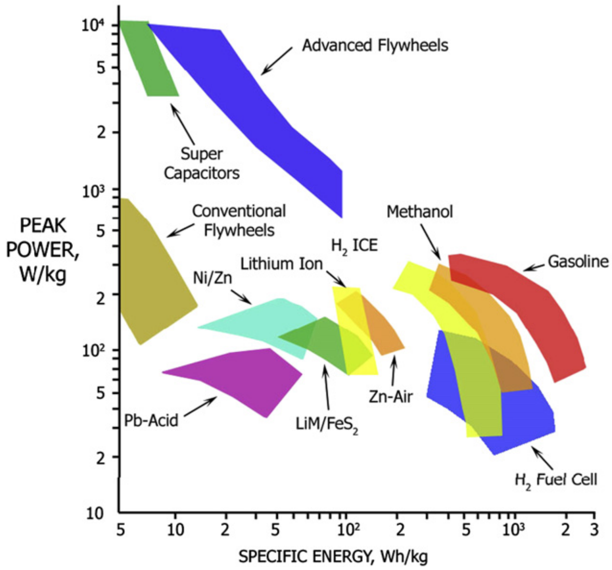

**Fig. 38.** The Ragone plot, comparing the energy and power densities of different options for energy storage, especially in transportation systems, including batteries, supercapacitor, flywheels and a number of fuels. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

## 8. Conclusions

We have summarized recent concerns regarding energy sources and consumption patterns, including the growing needs of a rising worldwide population that strives for better living standards and compete over limited resources, and the strong evidence that continuing use of fossil fuels without measures to reduce $CO_2$ emissions may lead to irreversible environmental damage resulting from global warming. The problem is particularly daunting because of the scale of energy consumption and its positive time derivative, and the global nature of the problem and proposed solutions. While we witness growing competition over limited resources, there is a need for global cooperation to formulate and implement solutions for harnessing more resources and mitigating the negative impacts of energy consumption. To match the consumption scale and universal impact, a portfolio of approaches that adopt to local conditions must be implemented. Solutions must be endorsed and implemented globally. Solutions must be technically grounded and rely on existing technologies or technologies under development. In to succeed in achieving large-scale change in a timely fashion, these technologically driven solutions must be encouraged by economic incentives and supported by public policies.

Conservation is of the highest priority. While targeting significantly better conversion (supply-side) and end-use (demand-side) efficiencies, conservation preserves energy resources and reduces the environmental impact. Almost in all applications, conversion efficiency can be improved, either by eliminating sources of losses or by taking advantage of waste energy. Improving conversion efficiency often requires complex hardware, exotic material, smart control technologies, etc, which is likely to raise the capital and operating cost. On the other hand, fuel saving could make up for some of this extra cost. Furthermore, the wide spread adoption of new technologies often leads to lower prices and encourages

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[26] New Delhi.

further innovation. Improvements in end-use efficiencies follow similar patterns.

Improvements in the accuracy of global climate modeling, supported by higher fidelity physical submodels; the implementation of more efficient simulation techniques capable of incorporating the impact of uncertainty; and faster computational hardware are necessary to refine predictions related to global warming and its impact on our environment. While historical records and current reliable predictions agree on the strong correlation between $CO_2$ emissions, its concentration in the atmosphere and the near Earth temperature, it is important to increase the reliability of predictions under different scenarios, both on a global scale and locally. Such improvements will lead to further confidence in the model results and urgency to implement solutions. Reliable and robust models are necessary components in defining effective solutions.

Carbon capture and sequestration from power plants, fuel production facilities and other energy intensive industries offers an opportunity to continue to use fossil fuels while mitigating their contribution to global warming. Given the plentiful supplies of coal and other heavy hydrocarbons, their cheap prices, and the massive infrastructure built around using these fuels or their derivatives, it is unlikely that a shift to alternatives will be sufficiently fast to avoid the predicted trends. Research, development and demonstration projects are necessary to enable the widespread adoption of CCS. Experience should improve the overall efficiency of these plans and reduce the cost of electricity produced at reduced carbon emissions. Partial CCS in retrofitted power plants, shift to low carbon fuels such as natural gas and syngas (produced by coal gasification with partial CCS) are parts of an effective transition strategy.

Nuclear energy and renewable resources are necessary components of the energy source mix, which are also carbon free. Nuclear power is a scalable resource that can satisfy larger fraction of electricity generation needs, but concerns over waste, safety and security must be addressed. Among sources of renewable energy, the form that currently contributes the most is biomass, which is used extensively as the primary source of energy in rural communities. Biomass-based fuels are contributing a very small fraction of transportation fuel needs, and expanding their share requires extensive effort to reduce their own form of environmental impact. Hydropower has been an important source where natural or man-made conditions permit. Only some forms of renewable energy are currently close to becoming economically competitive, such as wind, and others require large-scale storage that adds to the complexity of the system and cost of operation. Intensive effort is required on both fronts to increase the contribution of these sources to our energy demands. Renewable technologies that integrate seamlessly with the existing infrastructure offer opportunities for lower cost and speedy transition.

Solutions to the transportation challenges follow a similar strategy, with improvements in powertrain efficiency, especially through hybridization, and demand-side efficiency through, e.g., reduction of the size and weight of personal vehicles and further expansion of the public transportation services. Hybridization of the drivetrain is a transition to partial or full electrification of the transportation sector. Depending on the source of electricity, electrification can have significant impact on reducing carbon dioxide emissions from this sector. Effort to produce biofuels at a large-scale could contribute to some reduction of $CO_2$ emissions, but production technology must evolve to include cellulosic biomass and reduce $CO_2$ emissions during production.

## Acknowledgement

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