Chapter 53
Coal as a Component of Sustainable Energy Portfolio

Muhammad A.A. Khan and Ali Muhtaroğlu

Abstract Sustainable production and use of energy is currently a critical problem area for the world. The emissions from fossil fuels have valid environmental concern as reported by various scientific studies. This chapter reviews the geographical distribution of world coal reserves at the year-end 2010, and provides an overview of the opportunities for this most carbon-intensive fuel to be exploited in an environmentally benign way. Clean coal technologies (CCTs) are studied for both coal production and use. The potential of the CCTs is evaluated by focusing on five top coal producers of the world. Two of the examined producers are from the developed world, i.e., the United States and Australia. The remaining three are the developing countries, China, India, and South Africa. The status of the CCTs is outlined in the context of ongoing projects, and future prospects. Evidence for sustainable development capacity is provided with respect to "the three pillars of sustainable development," i.e., economic development, social well-being, and environmental sustainability. Economic appeal of coal-based energy is also demonstrated through comparative analysis against various other fuel options. The study concludes that unlike popular belief, production and use of coal can be relatively clean. Immediate deployment of CCTs can enable coal to remain in world energy mix at least until the end of this century. Incorporating the new and advanced technologies to coal production and use can reduce its emissions close to zero level in not-too-distant future.

Keywords Sustainable energy • Clean coal technologies • Sustainable development

M.A.A. Khan (✉)
Sustainable Environment and Energy System, Middle East Technical University, Northern Cyprus Campus, Kalkanlı, Güzelyurt, Mersin 10, Turkey
e-mail: tanazhar88@hotmail.com

A. Muhtaroğlu
Electrical and Electronics Engineering Department, Middle East Technical University, Northern Cyprus Campus, Kalkanlı, Güzelyurt, Mersin 10, Turkey
e-mail: amuhtar@metu.edu.tr

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Acronyms

BP	British petroleum
CBM	Coal bed methane
CCS	CO_2 capture and storage
CMM	Coal mine methane
DTI	Department of trade and industry, London
IEA	International energy agency
IGCC	Integrated gasification combined cycle
NMA	National mining association
USEPA	United States Environmental Protection Agency
WCA	World Coal Association
WCI	World Coal Institute

53.1 Introduction

Coal is considered to be the oldest fossil fuel used by mankind. It stands second with its 26.5 % share in world's primary energy as shown in Fig. 53.1 [1]. One reason of using coal is its vast geographical distribution across the world. However, accurate estimation of coal reserves is found to be a tricky exercise owing to the fact that data quality of these reserves is poor both on global and national levels. It is true that coal is abundant, affordable, safe and secure, and easy to transport and store, but it is also the most carbon-intensive fuel for electricity, and poses technological challenges when considered in the context of sustainable global growth.

It is observed that energy demand has grown strongly and will continue to increase, mainly in developing countries where energy is needed in economic growth and poverty alleviation. Renewable energy utilization is growing at a fast pace, but still represents only a small proportion of the world energy mix due to high cost, whereas coal has been heavily consumed for centuries. The price per unit energy from coal is relatively lower and more stable than other fuels. This is one of the main reasons coal has remained the fuel of choice for electricity generation at global level and is likely to remain so for several decades. Regardless of the well-recognized fact that coal is an environmentally harmful energy source due to CO_2 emissions 1.3 times more than oil and 1.7 times more than gas, the consumption of coal is expected to rise by 1.9 % per year between now and 2030 [2]. Almost three-quarters of the coal produced are used in fueling power or cement plants. Steel industry also utilizes it as a vital resource in production.

The use of fossil fuels in a sustainable manner is in debate for several years. In particular, coal's environmental impact always remains a key concern as one of the major contributors to climate change and global warming. Much work is already done over the last two decades to reduce the environmental impacts of coal, and research in this area is under way for making it part of a sustainable energy portfolio.

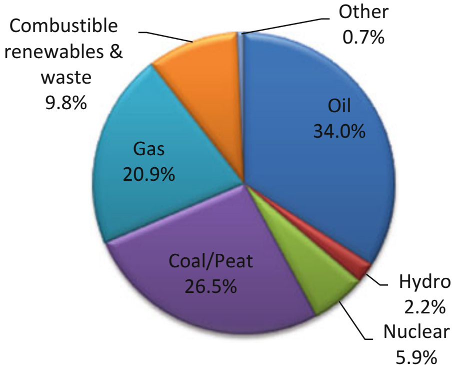


Fig. 53.1 Fuel shares of total primary energy supply in 2007 ~12 Gtoe (source: modified from [1])

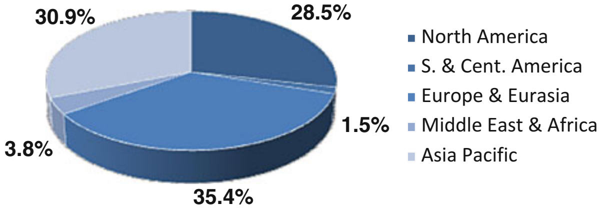
In this study, the sustainable development of coal is investigated. Five major coal-producing countries are selected for analysis, two from the developed (the United States and Australia) and the other three from the developing (China, South Africa, India) block of the world. An assessment of the global coal reserves is done based on the data collected by British Petroleum (BP) at the year-end 2010. Clean coal technologies (CCTs) are then briefly introduced, followed by a detailed discussion on the role of these technologies in coal production and use, their present status, and future prospects. The evidence of coal's sustainable development is provided in light of the three pillars of sustainability, namely, economic development, social well-being, and environmental sustainability. A comparative analysis is presented to demonstrate the economic appeal of coal-based energy compared to other fuel sources. Conclusions and recommendations are summarized at the end of the chapter.

53.2 Background: World Coal Reserves

Proved coal reserves at year-end 2010 are estimated at 860 billion tons (Gt), which represents about 118 years of production at the current rate. When compared with the estimates published in 2008, these numbers are 34 Gt and 4 years higher [3].

According to BP statistical review of world energy, the proved reserves are distributed in five regions of the world, namely, Europe and Eurasia, Asia Pacific, North America, the Middle East and Africa, and South and Central America as shown in Fig. 53.2 [4]. However, it is evident from the figure that world reserves for coal are concentrated in thirds. One-third is located in Europe and Eurasia (35.4 %), dominated by Russia (18.2 %), to which Germany (4.7 %), Kazakhstan (3.9 %), and Ukraine (3.9 %) can be added; one-third is located in Asia Pacific (30.9 %), where the reserves in China (13.3 %) alone are almost equal to the sum of reserves in India (7 %) and Australia (8.9 %); and one-third is located in North America (28.5 %), dominated by the United States (27.6 %). The Middle East and Africa represent less

Fig. 53.2 Distribution of proved reserves in 2010 (source: modified from [4])



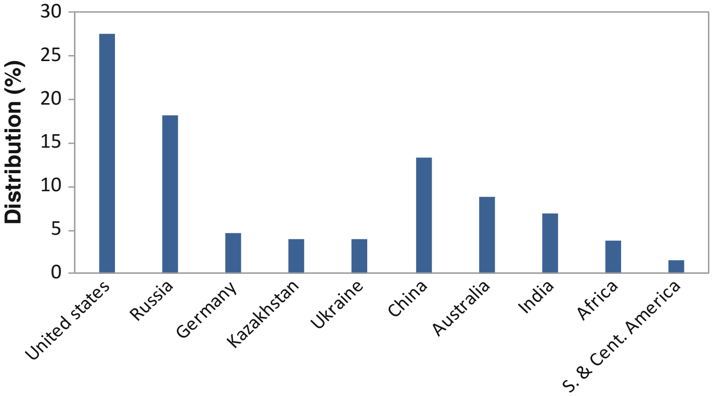


Fig. 53.3 World distribution of recoverable coal reserves at year-end 2010

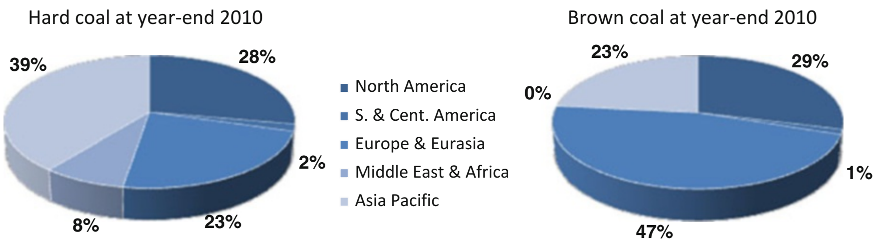


Fig. 53.4 Distribution of world coal reserves according to hard coal and brown coal

than 5 % of the total, with the bulk of coal wealth in South Africa. South and Central America holds only 1.5 % of world reserves. A detailed distribution of major reserves is shown in Fig. 53.3.

The total of 860 billion tons (Gt) breaks down into 405 Gt of hard coal (anthracite and bituminous coal) and 455 Gt of brown coal (subbituminous coal and lignite). The main application of hard coal is in the steel industry and power generation whereas brown coal is normally used as onsite fuel. With this classification of coal, the reserves are distributed in the world as shown in Fig. 53.4.

Clearly, Asia Pacific contains 39 % of hard coal, dominated by China (15.3 %), and Europe and Eurasia contains 47 % of brown coal, dominated by Russia

(23.6 %). North America shares equal amount of hard and brown coal (~28 %), and the Middle East and Africa area has hard coal (8 %) only. South and Central America area has 2 and 1 % of hard coal and brown coal, respectively.

53.3 Clean Coal Technologies

CCTs enable improvements in coal's performance as an energy source, and at the same time reduce its environmental impacts. These technologies contribute to different stages of coal production and use which may include extraction, preparation, storage, transportation, and use in power stations, steel mills, and other industrial applications. The following sections discuss the sustainable practices associated with coal production and use in detail.

53.3.1 Clean Coal Technologies in Coal Production

Coal is normally extracted by two different types of mining: "surface or open cast mining" and "underground or deep mining." The type of mining is selected based on the geology of the coal deposit. These processes cause harm to land, surface water, groundwater, and even air quality [5]. The impact can however be reduced through CCTs. Some of these techniques are already adapted in different parts of the world, and many of them are still in research and development phase.

For the purpose of this study, two broad areas of CCT in production are studied: (a) advanced coal preparation and cleaning techniques, and (b) coal mine methane (CMM).

Advanced Coal Preparation and Cleaning Techniques

The coal is extracted from mines with a rich content of mineral matter. It needs to be separated from these minerals for its proper functioning and end use. Normally the sequence of processes adapted for this purpose consists of coal pretreatment, cleaning, sizing and classification, dewatering and tailing treatments, and water clarification [6]. These processes result in high-quality processed coal that can be used commercially without environmental constraints. The plants fired by this coal in general have better environmental performance in terms of reduced SO_2, CO_2, and particulate emissions. The amount of combustion ash can also be decreased using these techniques.

Coal cleaning processes are usually categorized by the size of coal. According to technology status report of cleaner coal technology program [6], coal can be divided into coarse coal (>25 mm), small coal (25–3 mm), fine coal (<3 mm),

Table 53.1 Coal cleaning processes

Coal type	Cleaning process
Coarse coal	Dense medium separation
	Jig washing
Small coal	Jig washing
	Dense medium cyclone
Fine coal	Spiral concentration
	Teeter-bed separation
Ultrafine coal	Froth floatation

and ultrafine coal (<0.15 mm). The processes of cleaning different types of coal are listed in Table 53.1.

DTI London [6], under the cleaner coal technology program, categorizes the international markets for coal preparation and cleaning technologies as:

– Industrialized nations such as the United States, the UK, Australia, Germany, and South Africa, in which various coal preparation and cleaning techniques are in operation and are further researched by institutions and manufacturers.
– Nations in transition and development such as China, Ukraine, Kazakhstan, and Russia, in which lack of capital is a major constraint in technological advancement and indigenously developed tools with minimal processing are used for coal preparation and cleaning.

The fraction of extracted coal which is processed and cleaned varies from region to region. Similarly, the process and technology employed depend upon the type of coal available for cleaning. Table 53.2 summarizes the cleaning processes for the selected coal-producing countries. It is observed that by using these processes, power plants today emit 90 % less pollutant (SO_2, CO_2, particulates, and mercury) compared to plants in 1970s. Moreover, regulated emissions from coal-based power generation have decreased to nearly 40 % since 1970s, while the use of coal has tripled over the same time [7].

Coal Mine Methane

Methane can be extracted from coal seams that never experience mining, in which case it is called coal bed methane (CBM). Methane can also be extracted during and after the coal mining process, and referred to as CMM. CMM is simultaneously considered a mining hazard, a greenhouse gas, and a possible energy source [8].

According to International Anthropogenic Methane Emissions [9], underground coal mines liberate an estimated 29 to 41 $\times$ 10^9 m^3 of methane annually, of which less than 2.3 $\times$ 10^9 m^3 are used as fuel. There are several reasons to practice methane extraction during and after coal mining. In the first place, it increases mine safety. Fatalities and ventilation requirements can be reduced with improved working efficiency in less time. Another important reason is that it supports global sustainability. It is a clean fuel as compared to coal because it produces only half the

Table 53.2 Coal preparation and cleaning technologies (source of data: [6])

Country	Coal preparation and cleaning techniques
Australia	64 Plants in 1998, capacity >600 t/h Main technologies include 1. Dense medium (DM) separation 2. Teeter-bed separation 3. Column floatation for fine coal
China	1,570 small coal preparation plants, capacity <3,000 t/a 73 coal preparation plants >1.5 Mt/a Main technology used is jig washing
India	Total 24 coal preparation plants Main technologies include 1. Dense medium (DM) separation 2. Dense medium (DM) cyclone
South Africa	58 coal-processing plants in 1996 Main technologies include 1. Dense medium (DM) cyclones 2. Spiral concentrators since mid 1980s 3. Froth floatation
USA	Main technologies include 1. Dense medium (DM) cyclone (more than 50 %) 2. Jig washing 3. Froth floatation and spiral concentrators for fine coal 4. Column floatation for recovery and cleaning of ultrafine coal

Note: t/h and t/a in Table 53.2 refer to tons per hour and tons per annum, respectively

amount of CO_2 as compared to coal combustion on an energy equivalent basis, with no SO_2 and particulate emissions [10].

The selected countries for this study are among the top sources of CMM. Table 53.3 summarizes the amount of methane liberated annually by underground mining activities, the recovered amount, and its primary use. It can be observed that China is the primary source of CMM with 14 to 24 $\times$ 10^9 m^3 of methane, but the United States recovers more of the extracted methane than China, i.e., 700 $\times$ 10^6 m^3. India releases the least amongst all, but has potential for CMM. Some projects are in research and development phase in India, such as Moonidih and Sudamdih in Jharia Coalfields, and National Coal Company's CMM project.

53.3.2 Clean Coal Technologies in Coal Use

CCTs also play a significant role in efficient coal use. The sustainable use of coal is discussed under two categories in this study: (a) clean fuels from coal and (b) CO_2 capture and storage.

Table 53.3 CMM potential (source of data: [10])

Country	CMM potential
Australia	594 to 1,162 × 10^6 m^3 of methane are liberated 70 to 122 × 10^6 m^3 of methane are recovered Primary use: Electricity generation
China	14 to 24 × 10^9 m^3 of methane are liberated 561 × 10^6 m^3 of methane are recovered Primary uses 1. Heating and cooking at mine facilities and nearby residences 2. Used by the glass and plastic industry 3. Power generation
India	576 × 10^6 m^3 of methane are liberated No coal mine methane recovery programs are in place
South Africa	1.1 × 10^6 m^3 of methane are liberated Normally exploration is done not for the purpose of methane recovery
USA	4.2 × 10^9 m^3 of methane are liberated 0.7 × 10^9 m^3 of methane are recovered Usually sale to gas distributors to earn profit

Clean Fuels from Coal

Coal can be used sustainably by minimizing its direct combustion in the atmosphere. Coal has the potential to be converted into liquid and gaseous fuels, the combustion of which yields less pollutants than the combustion of coal itself. The conversion of coal into liquid fuels enables many countries to reduce their oil imports and at the same time reduce its environmental impacts. Coal-to-liquid conversion is found to be more promising compared to coal-to-gas conversions due to the cost and transportation issues associated with it.

Coal Liquefaction

Coal can be readily converted into a variety of liquid fuels which in turn offer a host of advantages. For example the liquid fuel derivatives of coal are ultra-clean, sulfur-free products, are low in aromatic hydrocarbons (such as benzene), and reduce vehicle emissions such as oxides of nitrogen, particulate matter, volatile organic compounds, and carbon monoxide [11]. One example of these fuels is dimethyl ether (DME). It is a domestic fuel, noncarcinogenic, and nontoxic to handle, and emits fewer amounts of carbon monoxide and hydrocarbons to the atmosphere. Some of the coal liquefaction projects from the countries under discussion are highlighted in Table 53.4.

Table 53.4 Coal liquefaction projects (source of data: [11])

Country	Coal liquefaction projects
Australia	Monash Energy Project Capacity: 62,000 bbl/day Products: Coal-derived diesel and other liquids Expected year of operation: 2010 Location: SE Australia
China	Shenhua Energy Group Project Capacity: 50,000 bbl/day Products: Jet fuel, gasoline, and diesel fuels In operation since 2007 Location: North China's inner Mongolia autonomous region
India	No coal-to-liquid (CTL) projects have been formally proposed yet but its high-ash, low-quality coals well suited to conversion
South Africa	Sasol CTL Project (I, II and III) Capacity: 112,000 bbl/day Products: Coal-derived fuels for vehicles and commercial jets In operation since 1955 Location: Sasolburg and Secunda
USA	DKRW Energy's CTL Project Capacity: 11,000 bbl/day and expected to rise by 40,000 bbl/day Products: Various fuels—primarily diesel Location: Medicine Bow, Wyoming

Coal Gasification

Coal gasification can provide an affordable energy supply with high efficiencies and near-zero pollutants. Normally, coal is converted to gas using integrated gasification combined cycle (IGCC). An IGCC plant uses up to 40 % less water, and 90 % of mercury emissions can be captured compared to conventional plants. Emissions of oxides of nitrogen (NOx) are reduced by at least a third, sulfur oxides (SOx) by more than two-thirds, and particulates down to almost zero [12].

An IGCC plant does not use conventional natural gas as fuel. Instead, it uses a synthetic gas produced via gasification of another feedstock which is normally coal or petroleum residuals. The IGCC plant breaks down the coal into its chemical constituents such as carbon monoxide (CO), hydrogen (H_2), and some other gaseous compounds, instead of burning it directly. The CO is converted to CO_2 and can be captured if there is a provision of doing so, but for conventional coal-fired plants, it is always emitted to atmosphere. The resulting gas is called synthetic gas (or syngas), consists mostly of hydrogen, and is used in power generation. Syngas possesses the ability of polygeneration, i.e., it can produce commercial by-products such as methanol, ammonia/fertilizer, hydrogen, and substitute natural gas [13].

IGCC is relatively a new technology, and different projects are in research and development phase. One of such projects is FutureGen, USA. This project claims to

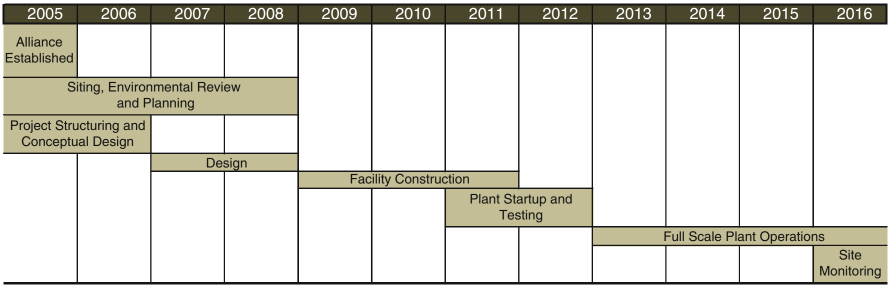


Fig. 53.5 FutureGen time line (source: modified from [12])

be the world's first coal-fueled near-zero emission power plant. According to World Coal Institute [12], the project will use coal gasification technology with combined cycle electricity generation and CO_2 storage. It is expected that the plant will be economically feasible by producing low-cost electricity and hydrogen from coal with almost zero emissions. A detailed time line of FutureGen is presented in Fig. 53.5.

CO_2 Capture and Storage

The amount of CO_2 is continuously increasing in the atmosphere due to energy production and use. According to World Energy Outlook [14], the global energy-related CO_2 emissions will be 57 % higher in 2030 than in 2005. In this alarming situation, CO_2 capture and storage is the only technology which seems capable of mitigating the greenhouse gas emissions, especially CO_2 emissions from large-scale fossil-fueled plants. Coal-fired plants can significantly reduce their emission by integrating CCS. This integration can be done in three ways, namely, pre-combustion, post-combustion, and oxyfuel combustion.

Pre-combustion capture involves gasification of coal prior to combustion as discussed earlier in sect. 3.2.1.2. The resulting CO_2 is then compressed into a supercritical fluid so that it can be transported for geological storage. Post-combustion involves separation of CO_2 from exhaust gases resulting from coal combustion. For oxyfueling the combustion of coal is carried out in an oxygen-rich environment, rather than air, without allowing nitrogen to enter into the combustion chamber. The resulting stream of CO_2 can easily be captured, compressed, and stored. However, this technique is still in the demonstration phase.

The coal producers are now working to incorporate CCS in their coal-fired plants. The current status along with future prospects of CCS is discussed for the five countries under consideration and the projects which are in development phase are briefly summarized in Table 53.5.

Table 53.5 CO_2 capture and storage projects (source of data: [14])

Country	CO_2 capture and storage projects	
Australia	1. ZeroGen Project Location: Brisbane, Queensland Capture method: Pre-combustion Expected year of operation: 2017	2. FutureGas Project Location: South Australia Capture method: Post-gasification Expected year of operation: 2016
China	1. China–Australia Collaboration Location: Huaneng, Beijing Capture method: Post-combustion	2. China–Japan Collaboration Location: Heilongjiang, NE—China Capture method: Post-combustion
India	Indian CO_2 sequestration Applied Research Network is established in 2007 No current project	
South Africa	South African center for Carbon Capture and Storage established in 2009 South Africa emits over 400 million tons of CO_2/year It is estimated that 60 % of these emissions can be captured	
USA	1. FutureGen Project Location: Meredosia, Illinois Capture method: Pre-combustion Expected year of operation: 2012	2. Texas Clean Energy Project (TCEP) Location: West of Odessa, Texas Capture method: Pre-combustion Expected year of operation: 2014

53.4 Coal and Sustainable Development

The extraordinary dependence of world on coal brings about the need of sustainability in its use. Sustainable development is a broad concept, and is founded on three pillars—economic development, social well-being, and environmental sustainability. Coal has an active participation in all three pillars and much work is in progress to exploit it in a more sustainable manner.

53.4.1 Economic Development

Coal is a major contributor in world's economy. According to World Coal Association [15], coal produces 41 % of world's electricity, which is double compared to its competitors, gas and hydro, and it is also used in 70 % of world's steel production today. Coal mining is done in over 50 countries and this industry employs around seven million people, 90 % of which are in developing countries [16]. Moreover, developing countries are found to be export oriented in the coal industry which helps them to earn foreign hard currency while saving in import costs. World Coal Association estimates that coal generates around $7 billion per annum in export revenues for developing countries and saves them $60 billion or more in energy import costs every year.

53.4.2 Social Well-Being

Adequate energy access to all is a global challenge today. According to World Energy Outlook [17], 1.6 billion people in developing countries do not have electricity and around 2.4 billion people rely on primitive biomass fuel for cooking and heating. Coal offers some solutions to these problems. For example, in China over the past 15 years, around 700 million people are served by coal-based electrification. The electricity production in China is raised by 1,000 TWh, 84 % of which is coal fired. Besides electrification, coal industries run on workforce from local communities in which they operate. These companies emphasize education and skill development programs. They contribute to school needs, or help administrators of the area by developing some management programs. An educated and skilled local community helps in attracting further investment and thus sustains the people even after mine closure.

53.4.3 Environmental Sustainability

The coal industry realizes that its extraordinary consumption may degrade the environment, and therefore measures are taken to improve the coal's environmental performance steadily. Power plant builders are now capable of working at an efficiency level beyond 40 % and are further trying to achieve 50 %. The greenhouse gas emissions can be expected to be lower by 10–20 % by operating power plants at these enhanced efficiencies. In its report "The role of coal as an energy source," WCI narrated that the United States has reduced its sulfur emissions by 3 % every year since 1980 despite rising coal use, and Germany has also reduced its NOx and particulate emissions by over 80 % since 1980s [16].

Figure 53.6 clearly demonstrates the movement of coal in sustainable energy portfolio. It can be observed that the technological advancements can reduce the CO_2 emissions from coal up to 99 %. As discussed earlier, some of the CCTs are already incorporated in coal production and use, and are able to reduce about 25 % of CO_2 emissions. However, significant research and development in newer CCTs is ongoing. It is expected that the advanced carbon capture and storage projects will be operational in around 10 years from now which can reduce the CO_2 emissions by ~99 %.

53.5 Economic Appeal of Coal-Based Energy

An important factor that keeps coal in the global energy portfolio is its superiority in providing a stable cost for electricity generation compared to other fuels. A comparative analysis is done by Morgan et al. to identify the most cost-effective form of energy production among nuclear, coal, natural gas, wind, solar, and hydro

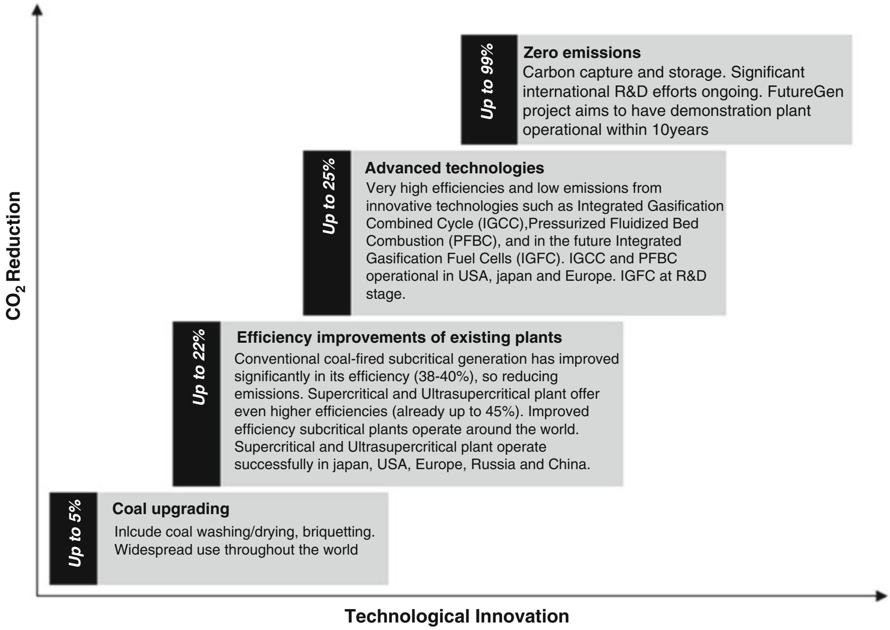


Fig. 53.6 Coal-fired route to CO_2 reduction (source: modified from [15])

[18]. Construction, production, and decommissioning costs (where necessary) are taken into account. The results of the analysis are shown in Fig. 53.7. Although hydroelectric is found to be most cost effective with 30 cents/kWh, it has some geographical and environmental limitations such as biodiversity impact and relocation of people. Coal and nuclear are nearly equal with 40 cents/kWh, but nuclear production has certain decommissioning cost and risks. Therefore, coal production and utilization using CCTs can be the most attractive option for energy generation since all other sources such as natural gas, wind, and solar have high cost per kWh.

53.6 Conclusions and Recommendations

The future global energy portfolio will include widespread use of coal as a primary energy source. The sustainability issues associated with this energy source are discussed in this chapter. The sustainable practices in both developed and developing countries are analyzed. The key conclusions and recommendations from this study are as follows:

- Coal plays an important role in sustainable energy systems for the foreseeable future due to plenty of advantages associated with it. CCTs are needed to be deployed immediately both in developed and developing world if coal is to remain in the global energy portfolio for later part of the century.

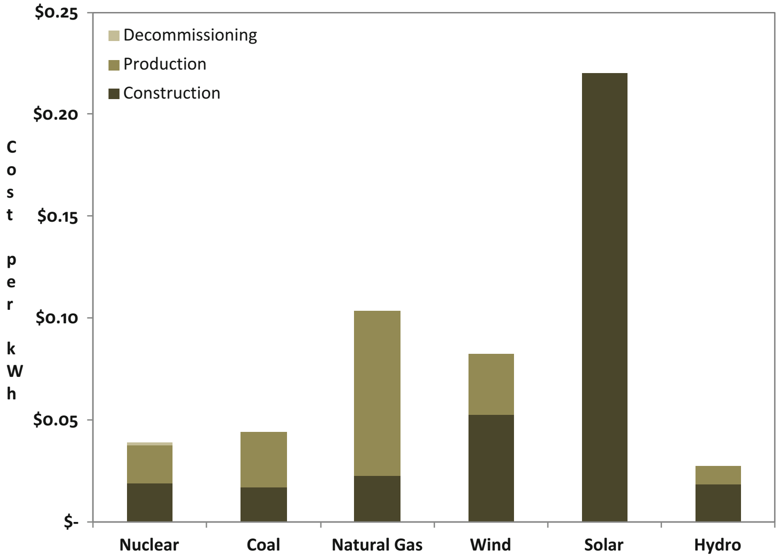


Fig. 53.7 Cost of electricity production per kWh (source: modified from [18])

- The techniques, such as coal preparation and cleaning, CMM, and coal-derived clean fuels, are already employed in different countries, and more advanced technologies like IGCC with carbon capture and storage (CCS) are under development to be operational in a couple of years.
- More improvements are required in environmental performance of the coal. Although improved coal technologies provide increased efficiency with reduced emissions to date, accelerated technological advancements can lead to near-zero emissions. An example of such a technology is FutureGen which was expected to be in operation by 2012.
- Coal has a great contribution in the three pillars of sustainable development. This development could be more effective by establishing well-defined policies specific to each pillar.

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