The importance of high efficiency low emissions technologies for sustainable coal utilisation

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ABSTRACT: Coal utilisation for power generation is facing many challenges including the need to limit greenhouse gas and non-greenhouse gas emissions, minimise water use, and ensure flexible operation. However, it is a key energy choice for developing countries because it is low cost and provides a reliable source of grid-based energy. There is a strong emphasis on its use in Asia and, increasingly, this is based on the introduction of high efficiency low emissions coal power systems, for which there continues to be significant ongoing deployment. At the same time there is ongoing innovative development to further improve overall performance and operational flexibility in order that intermittent renewable sources can be maintained on the grid. For the future, further transformational developments are underway that offer the prospect of maintaining robust coal-based units while also offering the prospect of low cost further reduction of greenhouse gas emissions.

KEYWORDS: clean coal utilisation; HELE technology; sustainability

1. Introduction

Global energy demand varies on a geographic basis. In many OECD regions, increases in energy use are small due to static populations, limited economic growth and established infrastructures. In contrast, in developing regions, especially Asia, energy use is increasing rapidly, with the need to supply adequate resources for rapidly rising populations while managing increasing urbanization and significant economic development. To put this in context, there are more people living in Asia than on the rest of the planet and that proportion will continue to increase with consequent needs for additional energy resources (World Economic Forum 2017).

There are three key issues to be considered, namely security of energy supply, economic competitiveness, and environmental issues including climate concerns. This trilemma represents an energy selection compromise as it is not possible to maximise all three criteria. In Western Europe, most countries have established anti-coal political positions and are seeking to close coal plants and replace them primarily with intermittent renewable energy resources such as solar and wind power. This approach is very expensive and requires reliable back-up power generation options to avoid major perturbations in grid stability. Such support is typically supplied by coal power plants (Wiatros-Motyka 2019)

In contrast, in the developing regions, especially Asia, there is a very strong recognition that sustainability is not just about climate issues. It also includes having access to robust, reliable and affordable energy sources that can have a key role in helping to lift people out of poverty. Coal fulfils all those criteria, which is why it is the energy source of choice in the majority of such countries.

From a sustainability perspective, coal utilisation impacts on many issues, as shown in Figure 1 (United Nations 2019)

Figure 1 UN sustainability goals and their applicability to coal production and utilisation.

In the developing world, coal use is already very significant and continuing to grow. Most of these coal power plants are young, are at least part owned by the governments and will continue to be used for decades to come. Many more such plants are being constructed (Barnes 2018). There are also worldwide development programmes to establish high efficiency, low emissions, low water use, coal power units, which can be operated on a flexible basis to meet rapid changes in demand.

2. The case for sustainable coal utilisation

Global energy needs are continuing to rise, which means that we will need all energy sources that are available to us, with maximum benefit being obtained through interconnection. At the same time, there is increasing urbanisation in developing countries and industrialising economies, with some 1 billion people without access to any power sources and a similar number who only have limited use. It is important to remember that, in such countries, energy use per capita is much lower than in the developed world. The provision of reliable grid-based power will help lift such people out of poverty, with consequent benefits such as improved education and job opportunities. Currently, such power can only be provided effectively by fossil fuel based systems.

Coal is readily available worldwide, low cost without the price volatility of oil and gas, and can be used for power generation, industrial applications such as cement and steel manufacture, as well as converted to high amenity products such as future fuels and high value chemicals (WEC 2018). Coal is the second source of primary energy in the world at some 30%, behind oil and ahead of gas, and the leading fuel for power generation at some 40%. However, it has a high carbon content, which raises concern about its potential contribution to global warming (Baruya 2014).

A great many developing countries have indicated that they intend to continue to use coal, since most cannot afford significant quantities of imported liquefied natural gas and do not recognise any major strategic grid-based benefits from the use of intermittent renewables. A realistic way forward is to encourage them to introduce high efficiency coal power options since these will require less coal per unit of power produced, with a corresponding decrease in CO_2 emissions. This can be achieved through the deployment of high efficiency low emissions (HELE) coal power plant and in due course, when market conditions are right, the application of carbon capture utilisation and storage (CCUS). Such an approach will be effective and allow us to limit future carbon emissions at a much lower cost while ensuring that the advantages of coal use are maintained. It is also possible to ensure levels of conventional pollutants such as PM, SOx, and NOx will meet ever tighter regulations as they are easily removed using state of the art low-cost technologies (Zhu 2016). It is important to recognise that technology suppliers and users certainly see the benefits of coal use technologies and there is a wealth of transformational development underway to achieve greater efficiencies while ensuring emissions of non-greenhouse gases remain lower than those that can be achieved by gas fired units. The current best efficiency level is some 47% (lhv, net basis), the exact values depending in part on plant location. As well as establishing units with higher steam pressures and temperatures, very innovative improvements are being taken forward to boost efficiencies to over 50%.

With regard to CCUS, the inclusion of such techniques will allow near-zero emissions to be achieved from a coal plant, while the captured CO_2 can be used in several applications, especially enhanced oil recovery. However, there is a need for government drivers to ensure commercial scale units will be established.

3. Current HELE coal fired power generation and beyond

A HELE coal power system comprises the essential components employed in all coal power systems, while operating at higher steam temperatures and pressures than conventional units, Figure 2. In particular, steam generated in the boiler is carried to a steam turbine that comprises a high-pressure (HP) turbine, an intermediate-pressure (IP) turbine, and one or more low-pressure (LP) turbines. Steam passes from one to the next in sequence. Further efficiency gains can be achieved by reheating the steam between the HP and IP turbines. This recycle can take place either once or twice, known as single and double reheat respectively. The latter provides a more efficient system but has a higher capital cost requirement.

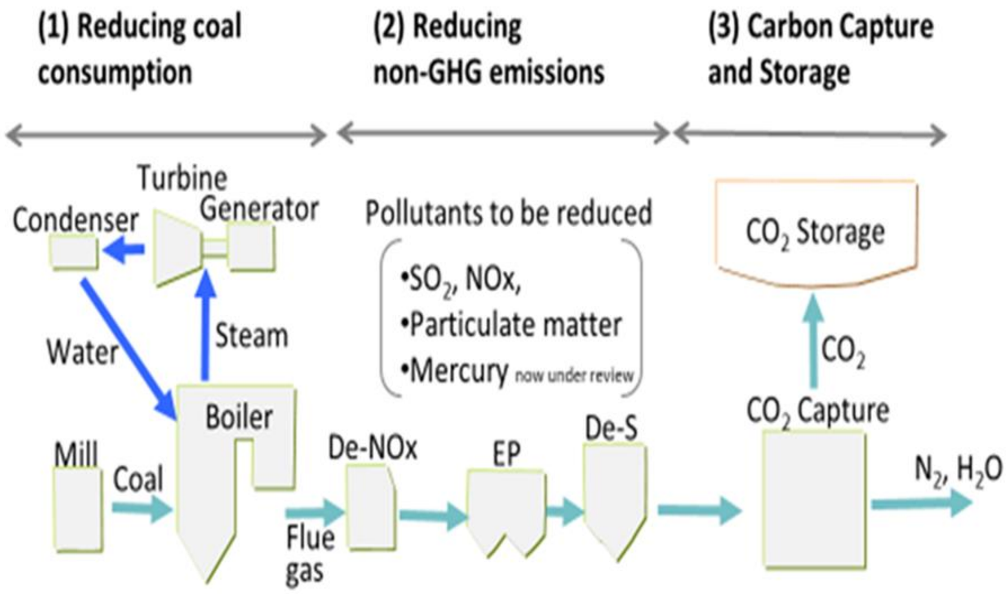

Figure 2 Schematic of a HELE coal power plant

3.1 Lower CO_2 emissions through higher efficiencies

A subcritical plant typically operates at steam temperatures up to 540ºC and has a thermal efficiency of between 30% and 39% (net, lower heating value basis), depending on the unit size, coal quality and local conditions. In order to achieve higher efficiencies, supercritical and, most importantly, ultra-supercritical (USC) coal-fired technologies have been developed. On large scale units (660-1000MWe) with USC steam conditions, a design thermal efficiency level of 45% to 47% has regularly been achieved depending on the exact conditions, Figure 3. The latest designs can achieve efficiencies close to 48% with some units under construction expected to achieve over 49% (net, lhv basis). This represents a >30% reduction in CO_2 emissions compared to the global average.

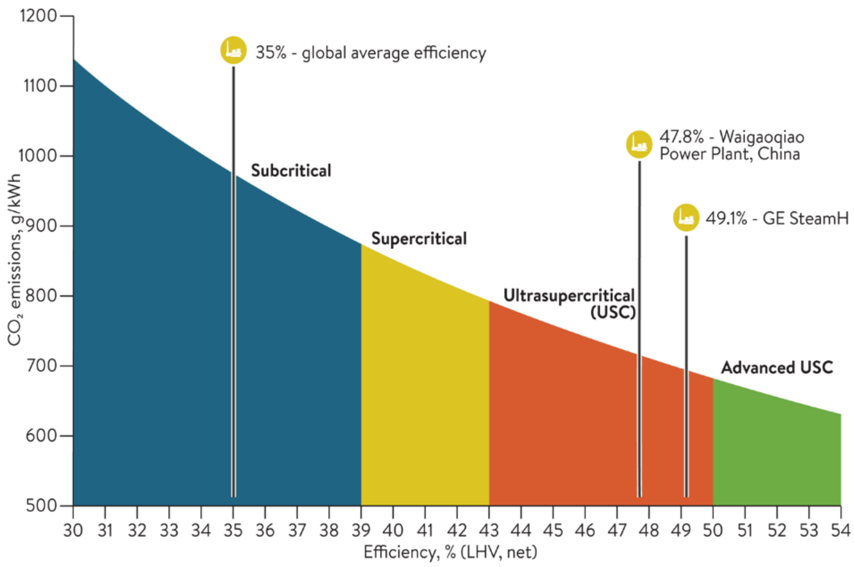

Figure 3 HELE efficiency and CO_2 emissions

The driver to increase the thermal efficiency of power generation, i.e. increase the amount of energy in the coal that is converted to electricity, is essentially an economic decision for which there is a trade-off between the capital and operating costs involved, and the risks involved. Thus, USC plants have higher capital costs than the conventional units because of the higher requirements of the steel needed to withstand the higher pressure and temperature. However, this is offset by costs savings due to the higher efficiency of the process. These include reduced coal use for a given electricity output, while the plant has a smaller footprint with respect to size of coal handling and emission control systems.

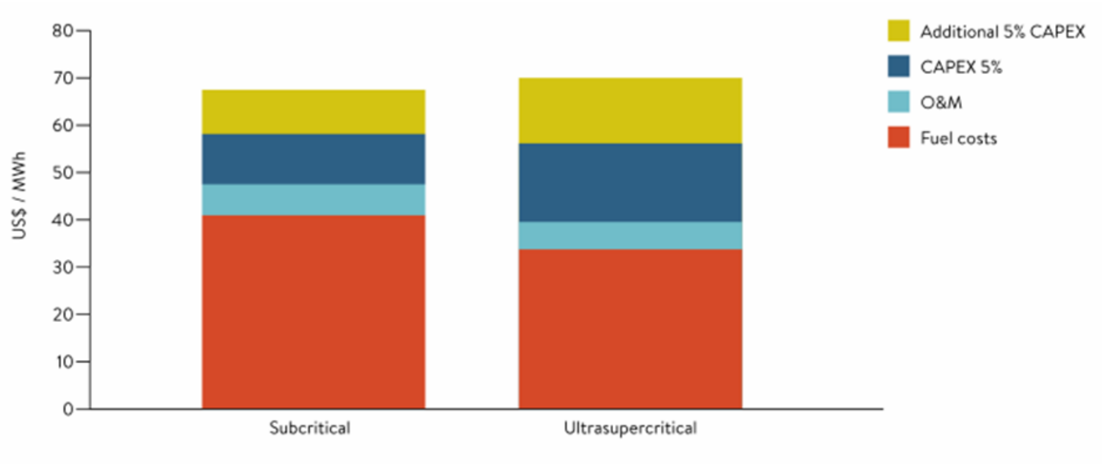

Figure 4 Full cost comparison of a subcritical and ultra-supercritical coal power plant in Asia (IEA 2017)

In Asia, for example, the overall cost for an USC coal power plant is lower than for a unit with conventional (subcritical) steam conditions (IEA 2017). Although the capital investment is greater, the coal cost is lower as less fuel is needed. That said, such a financial balance is sensitive to the cost of capital (Figure 4).

3.2 Market penetration for HELE coal power

HELE coal power technology refers to the commercially available widely deployed units with USC steam conditions. These are being deployed in some 17 countries worldwide, especially in China, Germany, Japan, which are also the countries most involved with technology exports worldwide. Table 1 shows the number and distribution of such plants either in operation or under construction in June 2018 (Platts 2018).

Table 1 Distribution of HELE coal power plants with USC steam conditions (Platts 2018)

REGION	IN OPERATION (MWe)	UNDER CONSTRUCTON (MWe)
Asia	224,203	88,228
Europe	19,208	4970
Middle East	0	2400
Eurasia	300	0
North America	665	0

3.3 Means to improve the environmental performance of coal power plants

Improvements in environmental performance are driven by the legal requirement to meet emission standards. The tightest are those set in China, as shown in Figure 5. Coal power plants in Eastern China were required to meet the ultra-low emission standards by 2017 and in Central China by 2018, while coal power plants in Western China are encouraged to achieve emissions that meet or are close to ultra-low emission levels. There are some exemptions for circulating fluidised bed combustion units that burn low grade fuels and wastes and down-fired W flame boilers that burn low volatile coals. These do not have to meet the ultra-low emissions standards but must meet the emission standards that came into force from 2012.

Pollutant (mg/m3)	Coal-fired power plant standard (from 2012)	Coal power plant ultralow standard	Gas-fired power plant standard
PM	20-30	10	5
SO2	50-200	35	30
NOx	100-200	50	50

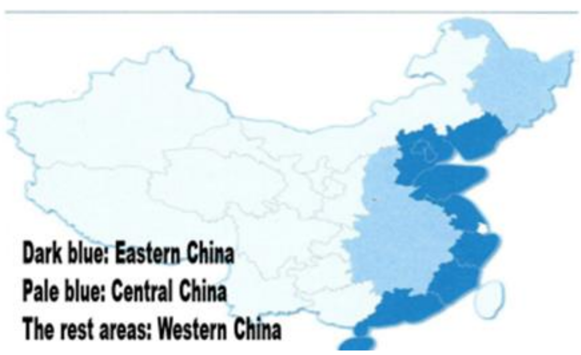

Figure 5 Coal power emission standards in China (Zhu 2016)

For the conventional pollutants (IEA 2014), the inclusion of appropriate well-proven flue gas cleaning units can meet all current requirements reliably and economically, such as electrostatic precipitators

(ESPs) or bag filters for fine particulates removal, flue gas desulphurization (FGD) for SO_2 control, together with combustion modifications and/or catalytic reduction systems for control of NOx, Figure 6.

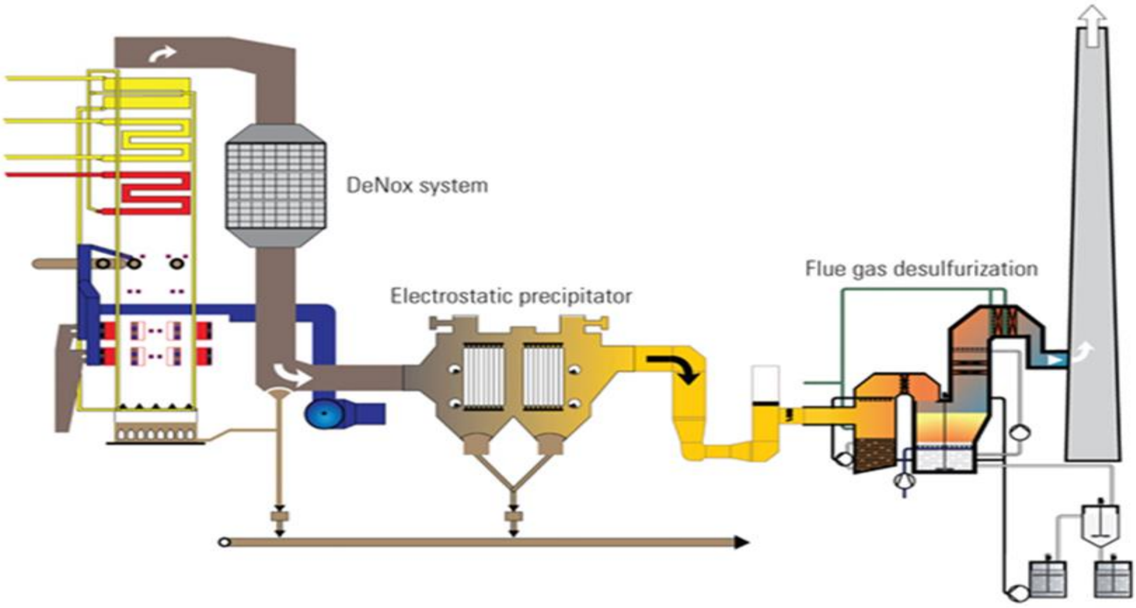

Figure 6 Schematic of the layout of conventional pollutant control systems (Feng 2015)

Fine particulates and NOx emissions control systems have a relatively small effect on the overall thermal efficiency of the power plant, while the inclusion of FGD can result in a one percentage point loss in thermal efficiency (Minchener 2012). The capital cost of these three measures can represent about one third of the cost of the unit when meeting the more stringent current standards.

Multipollutant technology offers the scope to combine all individual devices in to a single integrated system. This offers the significant potential of an efficient single solution that will reduce the land footprint and reduce the capital cost, thereby providing another step towards zero pollutant emissions. These systems are currently under development, particularly in Japan (METI 2013).

3.4 Ongoing technology developments and demonstrations

For the future, new higher temperature alloys are being developed, with R&D underway in China, Japan. India, Europe and the USA (Table 3). The aim is to achieve steam temperatures of 700-760 °C, which would mean that coal power plants could reach net thermal efficiencies of 50-55%, although a considerable amount of work remains to be done, with timelines to implementation for demonstration projects over the period 2021-2025.

Table 3 Scope of materials development programmes for advanced USC coal power plants

Programme	Steam temperature	Target efficiency (%, lhv, net)	Programme start date	Demonstration plant date and size
EU	700ºC	50	1998	2021 (500 MWe)
USA	760ºC	45-47 (hhv)	2000	2021 (600 MWe)
Japan	700ºC	>50	2008	2021 (600 MWe)
China	700ºC	46-50	2011	2021 (660 MWe)
India	700ºC	>50	2011	- 800 MWe)

While the aim of these demonstration programmes is to prove the performance of nickel alloy components for use with 700ºC steam conditions, an alternative approach is also being pursued. With more rapid advances in martensitic steels, it is possible that the steam temperature limits for advanced USC plant will be closer to 650ºC, since the materials burden is lower, while the shortfall efficiency has been limited through careful design and component integration. In this technology variant, GE is taking forward advanced USC technology, with steam conditions of 33 MPa/650ºC/670ºC, which is linked into their digital optimisation control system. The design cycle efficiency is 49.1% (net, lhv basis). Materials of construction include martensitic steels for most components with high nickel alloys in areas of critical importance such as steam pipes and the steam turbine inlet. The technology was launched in October 2017, with projects underway for advanced coal power plants in Turkey and China (GE 2018).

The third strand of this global R&D programme is to determine and implement overall design changes for the power plant, through the deployment of optimised individual components and their tighter integration. A key example is being championed by Prof Feng Weizhong, formerly employed by Shenergy but now operating in an independent capacity. He is leading the development and demonstration of an advanced USC technology, which incorporates all the improvements that he made on the Waigaoqiao No. 3 units, each of 1000MWe capacity, together with additional innovative components (Xing Z 2018). This is being built at the Pingshan Phase 2 site in Anhui Province. It comprises a 1350 MWe double reheat USC with an adapted steam turbine layout (Figure 7). In this arrangement the turbines are split into two trains. The front train, comprises the high-pressure turbine (HP) and intermediate pressure turbine (IP1) coaxial with one generator as the front unit. This is mounted on top of a two-pass boiler near the outlets of the tower type boiler steam headers, which is around 80-85 m above ground level. The rear train, which consists of the IP2 and the two LP turbines coaxial with another generator as the rear unit, remains in the conventional position, some 17 m above ground level. This approach minimises the lengths of the main steam pipe, cold reheat steam pipe, hot reheat pipesl and the cold reheat steam pipe. The shorter pipework represents a significant cost saving and reduces the pressure drop and temperature loss of steam from the boiler, which increases efficiency. There is close cooperation with Siemens, who supplied the adapted turbine, GE and the East China Electric Power Design Institute.

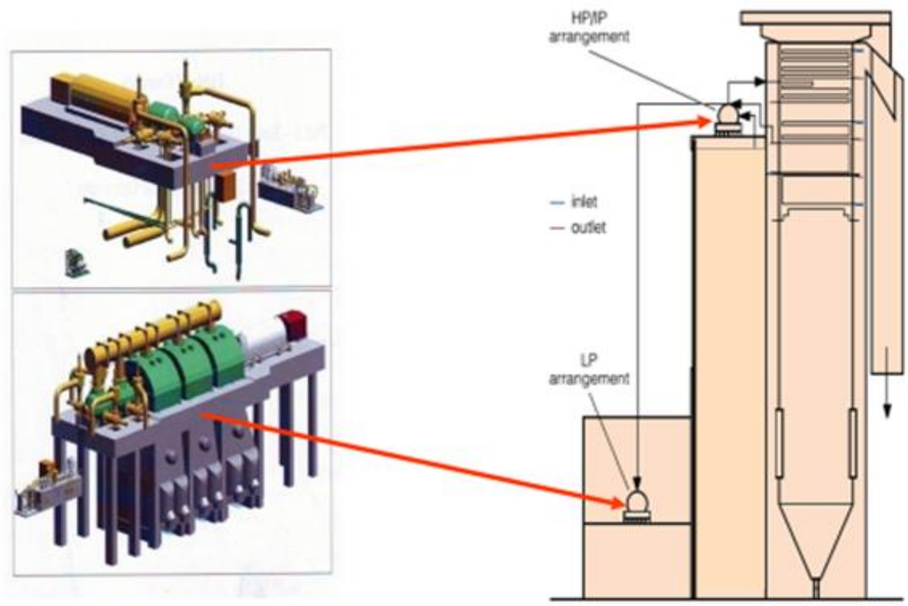

Figure 7 Schematic of the split turbine approach (Xing 2018)

Table 4 Design conditions for the Pingshan 2 1350MWe double reheat USC coal power plant with adapted steam turbine layout (Xing 2018)

Design condition	Expected output
Rated output	1350 MWe
Rated main steam flow	3229t/h
Max main steam flow	3416t/h
Main steam pressure/reheat steam I pressure/reheat steam II pressure	30MPa/9.17MPa/2.25MPa
Main steam temperature/reheat steam 1 temperature/reheat steam 2 temperature	600°C/610°C/620°C
Cooling water temperature	19°C

The other key requirement for coal and gas fired power plants is to provide stability of the grid systems due to the introduction of intermittent supply from wind and solar sources. A rising proportion of these renewables is reducing the inertia of grids, presenting challenges for stability and security of supplies. Consequently, coal and gas-fired power plants are having to operate at highly variable loads and turn on and off at short notice to keep grids stable. Thus the fossil fuel plants have to operate with greater resilience for high availability, have the capability for fast start-up and rapid ramp rates, the means to meet a wide load range with a lower minimum output, and be able to minimise the need for sudden shut-downs as these can be damaging and expensive. All this has to be done while maintaining efficiency as far as possible and ensuring emissions compliance. This operational approach was not envisaged when such coal plants were designed but retrospective changes and improvements has ensured that it can be achieved, albeit at some cost (Henderson C 2014, Wiatros-Motyka M 2019).

3.5 The role of CCS/CCUS in lowering carbon emissions

Carbon Capture, Utilization, and Storage (CCUS) is a combination of techniques that can remove CO_2 from the flue gas of a power plant or other industrial process and in principle from the atmosphere, followed by processing of the CO_2 either for utilization or for transportation and subsequent storage in secure geological formations (AIChE, 2018). As was indicated above, the introduction of HELE technologies can make significant reductions in CO_2 emissions; however, CCUS/CCS can achieve over 90% reductions. Various projections suggest that despite the adoption of alternative energy sources and energy efficient systems to reduce the rate of CO_2 emissions, if the Paris Agreement is to be achieved then CCUS/CCS should be included in the mitigations measures, otherwise the overall cost will be some 138% higher and it may prove impossible to achieve the reduction targets (IEA 2018) There is also no other cost-effective technology solution capable of delivering the deep emissions reductions needed across key industrial processes including steel, cement and chemicals manufacturing, oil and gas production, all of which will remain vital building blocks of modern society.

While the first generation CO_2 capture techniques, which include a solvent based process, pipeline transportation of CO_2 and its use to enhance oil recovery from declining wells, have been shown to work well, albeit at limited scale, the consequence is an operational efficiency penalty and a major capital costs increase for the power plant or other industrial process. This raises the cost of energy and while CO_2 enhanced oil recovery will provide a valuable income stream, some form of financial subsidy will be necessary especially when CO_2 storage rather than utilisation is undertaken. This suggests that the technology is unlikely to be introduced at commercial scale without regulatory pressure. Equally important, while the first generation options are being taken forward, it is also critical to address various scientific, economic and societal aspects to ensure successful development and implementation of further CCUS technology options that are not yet ready for demonstration let alone commercial deployment but which appear to have potential advantages (Qian 2018, IChemE 2018, Lockwood 2018).

4. A way forward

Globally, the need for a continued supply of secure and affordable energy will increase as demand continues to grow. As such, all available energy sources will need to be used to meet demand, with newer options such as renewables supplementing the traditional fossil fuels of coal, gas and oil (Crooks 2019). At the same time, societal drivers are requiring an increasing emphasis on environmental sustainability such as clean air and reduced carbon emissions, as is reflected in the United Nations Sustainability Goals. The production and use of coal can be linked to each of these challenges.

There is no one-size-fits-all solution to the environmental sustainability challenges. Many OECD countries have added intermittent renewables to the overall energy mix, often at the expense of coal. In contrast, while some renewables will be used, developing countries will will continue to use coal and are unlikely to include CCUS under current commercial conditions. Consequently, to start to limit carbon emissions, there is a need to establish a staged approach. This is based on encouraging and supporting developing countries to introduce HELE coal power technology either as retrofit or new build options, preferably based on USC technology and in due course advanced USC as the development activities reach maturity. This can be followed by the addition of CCUS/CCS on such units when the business case is right.

Many nations see coal as a key part of their ongoing strategic energy mix and this is reflected in their National Determined Contributions to reducing carbon emissions as signatories of the historic Paris Agreement (UNFCCC 2019). Thus, Afghanistan, Bangladesh, Bosnia and Herzegovina, China, Egypt, Georgia, Ghana, India, Indonesia, Japan, Kazakhstan, Kenya, Mongolia, Montenegro, Myanmar, Nigeria, North Korea, Pakistan, Philippines, Republic of Macedonia, South Africa, Turkey, United Arab Emirates, and Vietnam all identified a role for HELE coal power technology in their NDCs. Between them these countries account for over half of global coal power carbon emissions. In addition, nations including Bahrain, Canada, China, Egypt, European Union (currently representing 28 countries), Iran, Iraq, Malawi, Montenegro, Norway, Saudi Arabia, South Africa, United Arab Emirates, and USA made either direct or indirect reference to CCUS/CCS in their NDCs.

5. Conclusions

Even with the drive to push the introduction of intermittent energy sources such as solar and wind power, coal currently provides 41% of the world's electricity and is an essential raw material in the production of 70% of the world's steel and 90% of the world's cement. It is set to remain a significant and integral part of the global energy mix for well into the future.

To move towards near zero coal power, new plant should be based on the deployment of ever improving HELE technologies with the scope to deploy CCUS in due course

National governments should support the deployment of HELE technologies as part of an emissions reduction strategy while also determining a coherent business model to ensure deployment of CCUS

With the rise of intermittent renewable power, coal fired plants now have to be ever more flexible, with the need for fast ramp response times and limited operation at maximum load.

In many parts of the world, water utilisation for power production is becoming an issue, with countries introducing legislation that requires utilities and other industrial users to minimise water usage, maximise water recycling in order to meet new environmental regulations, which will impact to varying degrees on operational efficiencies.

The technology development is moving rapidly, to take forward the advanced USC concepts while beyond that are some interesting and innovative alternative systems for which development and planned demonstration are underway.

The IEA Clean Coal Centre will continue to maintain a watching brief on all of these issues, which will be reported to all stakeholders through its assessment study reports, its various dissemination activities, and its outreach programme. As noted above, this is based on ensuring complementarity with the United Nations Sustainable Development Goals (IEA Clean Coal Centre 2018).

7 References

AIChE (2018) Carbon Capture Utilization and Storage. Available from: www.aiche.org/ccusnetwork/what-ccus (2018)

Barnes I (2018) Hele perspectives for selected Asian countries, IEA Clean Coal Centre CCC/287 (June 2018)

Baruya P (2014) Coal reserves in a carbon constrained future. IEA Clean Coal centre CCC/233 (March 2014)

Feng W (2015) Developing green, highly efficient coal-fired power technologies. ASME 2015 Power Conference, San Diego, California, USA, June 28–July 2, 2015

GE (2018) Smarter. Cleaner. Steam. Power. Available from: www.ge.com/content/dam/gepower-steam/global/en_US/documents/2018-Steam-Power-Product-Catalogue.pdf (2018)

Henderson C (2014) Increasing the flexibility of coal-fired power plants IEA Clean Coal Centre CCC/242 (September 2014)

IChemE (2018) Update on the Demonstration of the Allam Cycle. Available from: https://www.google.co.uk/search?q=Liekly+efficiency+for+coal+fuelled+Allam+Cycle&rlz=1C1GCEA_enGB745GB745&oq=Liekly+efficiency+for+coal+fuelled+Allam+Cycle&aqs=chrome..69i57.17363j1j7&sourceid=chrome&ie=UTF-8 (11 April 2018)

IEA (2014) Emissions reduction through upgrade of coal-fired power plants. Available from: www.iea.org/publications/freepublications/publication/PartnerCountrySeriesEmissionsReductionthroughUpgradeofCoalFiredPowerPlants.pdf (2014)

IEA (2017) Full cost comparison of a subcritical and ultra-supercritical coal power plant in Asia (2017)

IEA (2018) IEA and UK kick-start a new global era for CCUS. Available from: www.iea.org/newsroom/news/2018/november/iea-and-uk-kick-start-a-new-global-era-for-ccus.html (November 2018)

Lockwood T (2918) Overcoming barriers to carbon capture and storage through international collaboration, IEA Clean Coal Centre CCC/284 (March 2018)

METI (2013) Advancing Highly Efficient Technology and Environmental Performance. Available from: www.meti.go.jp/english/publications/pdf/journal2013_10a.pdf Ministry of Economy, Trade and Industry of Japan (2013)

Minchener (2012) Non-greenhouse gas emissions from coal-fired power plants in China. IEA Clean Coal Centre CCC/196 (April 2012)

Platts (2018) World electric power plants database. Available from www.spglobal.com/platts/en/products-services/electric-power/world-electric-power-plants-database (June 2018)

UNFCCC (2019) The Paris Agreement and NDCs Available from: https://unfccc.int/process/the-paris-agreement/nationally-determined-contributions/ndc-registry (January 2019)

United Nations (2019) About the Sustainable Development Goals. Available from: www.un.org/sustainabledevelopment/sustainable-development-goals/ (January 2019)

WEC (2018) Coal. Available from: https://www.worldenergy.org/data/resources/resource/coal/ (World Energy Council 2018)

Wiatros-Motyka M (2019) Power plant design and management for unit cycling and load fluctuation IEA Clean Coal Centre report in preparation (January 2019)

World Economic Forum (2017) More people live inside this circle than outside it - and other demographic data you should know. Available from: www.weforum.org/agenda/2017/07/more-people-live-inside-this-egg-than-outside-of-it-and-other-overpopulation-data/ (July 2017)

Xing Z (2018) Need details of her recently published paper in Modern Power Systems (I think)

Zhu Q (2016) China – policies, HELE technologies and CO2 reduction, IEA Clean Coal Centre CCC/269 (September 2016)

Zhu Q (2018) developments in CO2 utilisation technologies, IEA Clean Coal Centre CCC/290 (October 2018)