# Interplay of technologies for effective, flexible power grid operation

BRIEFING DOCUMENT FOR THE UNECE GROUP OF EXPERTS ON CLEANER ELECTRICITY SYSTEMS

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# SUMMARY

Global energy availability is very heterogenous with differences in the scope for utilisation between the prosperous OECD countries and most of the rest of the population. There is a vast disparity between those who have access to robust, reliable electricity and the developing nations that are still seeking some form of energy security and acceptable environmental conditions, in line with the United Nations Sustainable Development Goals. Consequently, while many OECD countries are focussed on achieving net zero carbon neutrality by 2050, in contrast, the nearer-term focus of the majority of the world's population is trying to ensure that there is access to robust, reliable and affordable electricity sources that can have a key role in helping to lift them out of poverty.

From a strategic energy perspective, there are three 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 OECD Western Europe, for example, most countries have established anti-coal political positions and are seeking to close coal plants and replace them primarily with intermittent variable renewable energy (VRE) resources, namely solar and wind power. Globally, this approach is currently unique since in other regions, especially those with developing nations, there tends to be a broader energy mix being established, comprising a combination of VRE and fossil fuel power plants, with the latter tending to be coal based due to lower fuel and infrastructure costs than either gas or biomass. Coal is a used by most of the developing nations as it is readily available, has low price volatility and there are technology variants that will burn it at high efficiency with low conventional emissions.

In many regions, especially Asia which is home to over 50% of the global population, there has been a rapid and significant demand for high efficiency low emissions (HELE) coal power plants. These burn less coal for each unit of energy output compared to traditional units, with a corresponding reduction in $CO_2$ and conventional (PM, $SO_2$, NOx) emissions. As such, the $CO_2$ emissions intensity is lower in regions where HELE technology is operational. 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. There are also worldwide development programmes to establish yet higher efficiency, lower emissions, low water use, coal power units, which can be operated very effectively on a flexible basis to meet rapid changes in demand.

From an operational perspective, the inclusion of VRE sources to power the grid is a major challenge. Although effectively zero carbon energy sources with low unit costs on a Levelized Cost of Electricity basis, solar and wind are not especially suited due to their intermittent availability. On their own, it is not possible to ensure total grid stability and the problem becomes worse as their capacity on the grid is increased. As the VRE capacity is increased on the grid there are very real risks that consumer demand cannot always be met and that total system costs will increase to levels far higher than suggested by the LCOE values. Although battery storage has been suggested as the means to provide much needed inertia to stabilise the grid, in reality it can at best help to even out the demand curves and, currently, cannot provide the means to substitute for the loss of sun and wind, arising from the vagaries of these sources. Consequently, not only are the total system costs very high but the system cannot function in a secure stable state without being linked to reliable back-up power generation options.

In order to address this operational challenge, there is a need to include some form of dispatchable generation. This refers to sources of electricity that can be used on demand and dispatched at the

request of power grid operators, according to operational needs. The proven options are based on coal or gas and to a lesser extent biomass. Dispatchable generators can either be turned on or off and can adjust their power output according to requirements. Thus, when the grid system is integrated to ensure an interplay of coal (or gas) and VRE sources, the dispatchable power source can be readily adjusted to balance the grid. This linking of dispatchable power with VRE provides the necessary inertia to avoid outages due to the intermittency of the VRE input. Equally important, such systems can always meet demand. Consequently, from a grid perspective the primary interplay is the combination of dispatchable power, which can be provided by either coal, gas or biomass with VRE sources Although not yet in place, there is a strong strategic case to introduce CCS onto the dispatchable power source to ensure that this becomes a very low $CO_2$ emitter.

There are other opportunities, in this case for integration of VRE sources with individual coal fired power plants. These approaches are technically adequate and allow the full range of the power plant's operating range to be achieved. The use of concentrated solar power provides scope to produce additional steam that can either boost power production (solar boost) or can be used to reduce coal use (coal reducing mode). However, under current market conditions they tend not to offer large scale and geographically diverse deployment opportunities and to date take-up of the technology has been limited.

Similarly, gas can be cofired in coal power plants and this has positive benefits, including lower conventional emissions. However, as with the previous option, the benefits do not necessarily justify the investment costs and again technology take-up is limited.

Finally, the cofiring of coal with sustainable biomass offers an alternative way forward. This can provide a relatively small reduction in $CO_2$ emissions as the usual option is to limit the renewable energy input thereby avoiding major power plant modifications. However, in developing countries, the renewable input can comprise agricultural residues that otherwise would most likely be burnt indiscriminately in the fields. As such, it provides a means to eliminate renewable energy induced air quality problems, which has significant attractions. That said, it is a technology variant that will require some level of subsidy since sustainable biomass tends to be more expensive than coal. In those countries where coal use is the preferred option and there are supplies of biomass available, this variant seems likely to prove attractive.

Establishing CCS/CCUS is currently seen as expensive relative to the introduction of VRE sources that have low unit costs on a LCOE basis. However, as the proportion of VRE sources increases, the total system costs increase rapidly to the point where the inclusion of CCS/CCUS is seen as a more attractive option. There is growing evidence that not only does the interplay of coal with CCS together with VRE result in lower total system costs, it can ensure that all system demand profiles can be achieved, unlike the case where VRE only is considered.

Consequently, there is an overwhelming need to support coal (or gas) with CCS/CCUS as a low carbon option for the interplay with VRE sources on the grid. Any major projects of this type need to be positively supported by high profile champions both to ensure government support but also to maintain momentum and interest with the general public. They need to present a compelling vision of the key role that CCS/CCUS needs to fill in ensuring a successful move towards carbon neutrality. This must include building the global case for CCS/CCUS so that it is positively included and acted upon as part of national agendas. This represents a far greater impact than has been achieved to date.

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# 1. INTRODUCTION

There are major changes taking place in many regions of the world as intermittent variable renewable energy (VRE) sources, namely solar and wind, are introduced into the power generation grid system alongside the traditional fossil fuel sources such as coal and natural gas. Although effectively zero carbon energy sources, solar and wind are not especially suited due to their intermittent availability, which currently requires the use of fossil fuel power plants to provide grid stability. As the VRE capacity is increased on the grid there are very real risks that consumer demand cannot always be met and that total system costs will be far higher than suggested previously.

The continued development of high efficiency low emissions (HELE) coal power plants offers a reliable and stable approach to power generation, Section 2. However, while it is a key dynamic in improving the $CO_2$ intensity of coal power plants, for the long term it must be a considered a high carbon option. Currently, coal power (both HELE and less efficient alternatives) is being used to successfully stabilise the grids by providing dispatchable power that counters the inherent instability of VRE, as set out in Section 3. Should these coal-based units be combined with carbon capture and storage/utilisation (CCS/CCUS) these can achieve near zero carbon emissions and still provide grid stability when VRE sources are included, Section 4. Besides this interplay of technologies, there are also other options that can be considered for combining the use of coal with lower and near zero carbon fossil fuels such as gas and some renewable options, including integration of these sources with coal power plants, which are considered in Sections 5, 6 and 7. How these various developments and interplay of technologies might be taken forward are considered in Section 8.

## 1.1 Geographical background for the UNECE

The UNECE region covers more than 47 million square kilometres (UNECE 2020a). It comprises 56 Member States, which includes the countries of Europe together with countries in North America (Canada and United States of America), Central Asia (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan) and Western Asia (Israel).

The UNECE region is home to 17% of the world population. It includes some of the world's richest countries, as well as countries with a relatively low level of development. This diversity in the levels of development represents a challenge to UNECE, as it must respond to the expectations of its different members. However, it is also an advantage, as it encourages the sharing of experience and knowledge, as well as a guarantee of financial and technical aid to countries in need.

## 1.2 Diversity and the energy trilemma

There are three key issues to be considered, namely security of energy supply, economic competitiveness, and environmental issues including climate concerns, Figure 1.

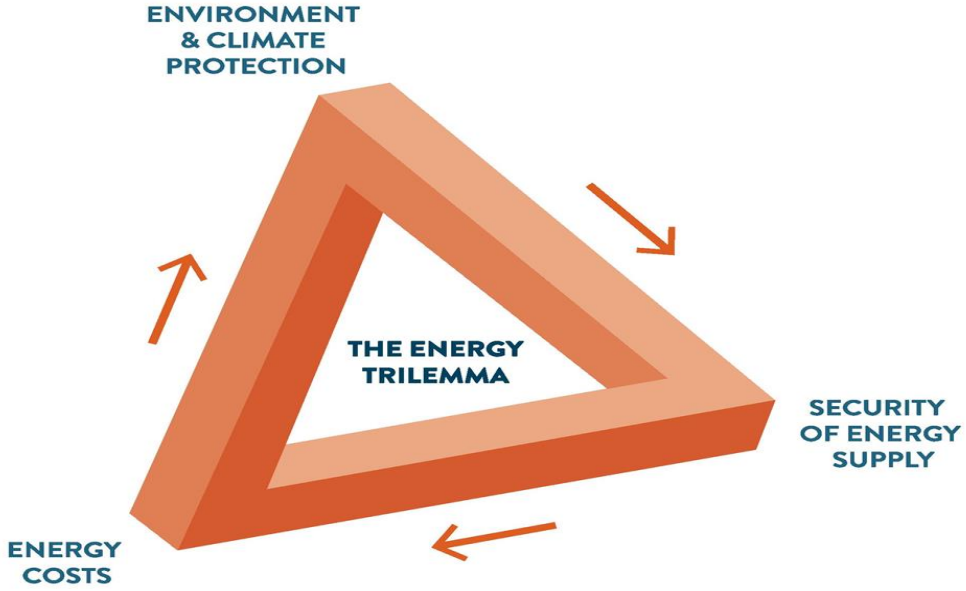



Figure 1 Key criteria of the energy trilemma (Baruya 2018)

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 variable renewable energy (VRE) resources such as solar and wind power. The total system costs of this approach are very expensive while also requiring 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 (UNECE 2020b). 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). Coal fulfils those criteria, which is why it is the energy source of choice in many such countries. Indeed, in the developing world, coal use remains very significant and is 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. 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. CURRENT HIGH EFFICIENCY LOW EMISSIONS COAL FIRED POWER GENERATION AND BEYOND

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

A great many developing countries have indicated that they intend to continue to use coal. 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 and storage/utilisation (CCS/CCUS). Such an approach will be an effective way to limit future carbon dioxide emissions at a much lower cost than alternative approaches 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 technologies (Zhu 2016). Technology suppliers and users certainly see the benefits of coal use and there is transformational development underway to achieve greater efficiencies while emissions of non-greenhouse gases remain at very low levels. The current best efficiency level is some 49% (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%.

## 2. 1 Technology overview

A HELE coal power system comprises the essential components employed in all coal power systems, while operating at higher ultra-supercritical (USC) steam temperatures and pressures than conventional units, 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.

## 2.2 Market penetration for HELE coal power systems

This technology has been primarily established in Asia, having first been deployed by Japan and then taken forward extensively in China who have since enabled deployment in other parts of the region. There has also been a significant introduction in Europe, as shown in Table 1.

Table 1 Distribution of HELE coal power plants with USC steam conditions (Platts 2020)

| Region | In operation (MWe) | Under construction (MWe) | Total (MWe) |
|---|---|---|---|
| Asia | 269511 | 62939 | 332450 |
| Europe | 22768 | 1410 | 24178 |
| Middle East | 1320 | 3720 | 5040 |
| Africa | 1386 | 0 | 1386 |
| Eurasia | 300 | 0 | 300 |
| North America | 665 | 0 | 665 |

## 2.3 Lower $CO_2$ emissions through higher efficiencies

The higher the efficiency of a coal power plant, the less coal needs to be used to produce each unit of electrical output, as shown in Figure 2. Efficiencies over 49% (net, lhv basis) are available on a commercial basis while ongoing developments should enable values close to 55% to be achieved within the near future.

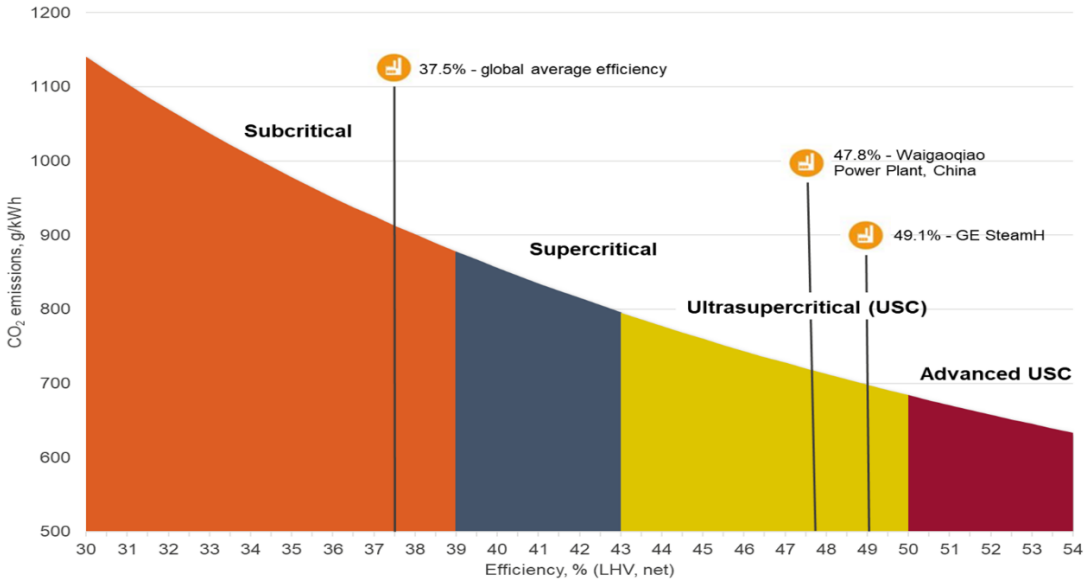



Figure 2 Relationship between coal power efficiency and $CO_2$ emissions

(Lockwood 2020)

## 2.4 Means to achieve high environmental performance of coal power plants

Improvements in environmental performance are driven by the legal requirement to meet emission standards. The tightest are those in China, as shown in Table 2. 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.

Table 2 Coal power emission standards in China (Zhu 2016)

| Pollutant ($mg/m^3$) | Standard from 2012 | Ultralow standard | Gas fired power standard |
|---|---|---|---|
| PM | 20-30 | 10 | - |
| $SO_2$ | 50-200 | 35 | 30 |
| NOx | 100-200 | 50 | 50 |

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. Multipollutant technology offers the scope to combine all individual devices into 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).

### 2.5 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 (Lockwood 2019)

| National programme | Steam temperature (°C) | Target efficiency (%, lhv, net) | Programme start date | Demonstration plant date and size |
|---|---|---|---|---|
| EU | 700 | 50 | 1998 | - |
| USA | 760 | 45-47 (hhv) | 2000 | 2021 (600 MWe) |
| Japan | 700 | 50 | 2008 | 2021 (600 MWe) |
| China | 700 | 46-50 | 2011 | 2021 (600 MWe) |
| India | 700 | >50 | 2011 | 2025 (800 MWe) |

While the aim of these demonstration programmes is to prove the performance of nickel alloy components for use with 700°C steam conditions, an alternative approach is also being pursued by GE. This is based around the rapid advances in martensitic steels, which would set the steam temperature limits for advanced USC at closer to 650°C. The materials choices would be less expensive than nickel steels while the shortfall in efficiency due to lower temperature steam conditions would be limited through careful design and component integration. With this technology variant, GE is taking forward advanced USC technology with steam conditions of 33 MPa/650°C/670°C, which is linked to 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 the Chief Engineer at 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 (Feng 2015; Minchener 2020).

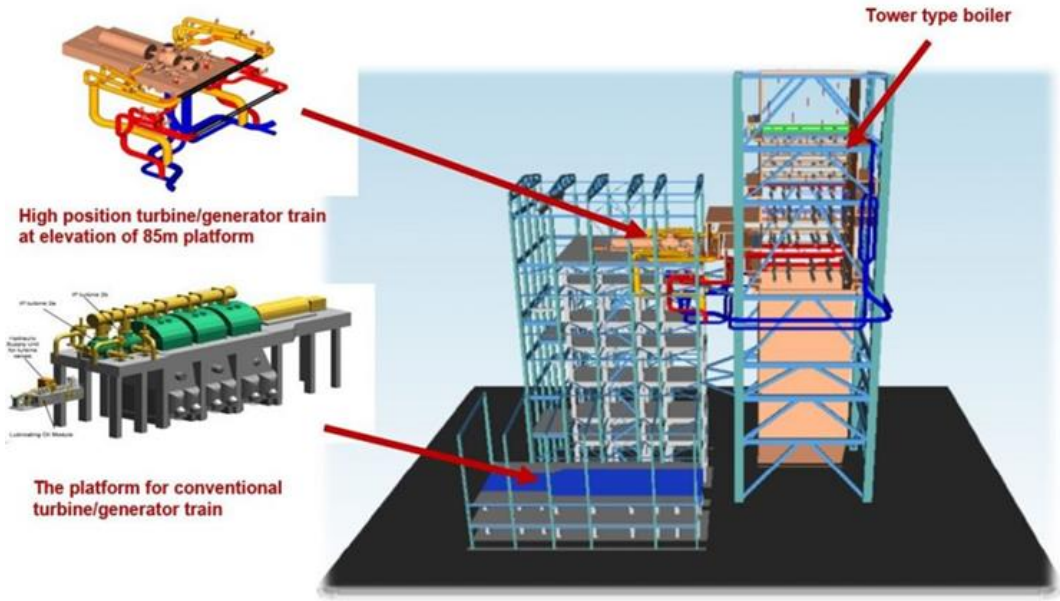



Figure 3 Schematic of the split turbine approach (Minchener 2020)

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 3). 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 length of the main steam pipe, cold reheat steam pipe, hot reheat pipe 1 and the cold reheat steam pipe. This 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.

Table 4 Design conditions for the Pingshan 2 1350MWe double reheat USC coal power plant with adapted steam turbine layout (Minchener 2020)

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

The estimated efficiency that should be attainable from this technology variant when it begins operation later in 2020 is greater than 50% (Minchener 2020). Should subsequent designs be adapted to incorporate 700°C USC steam conditions, efficiencies in excess of 54% (net, lhv basis) should be feasible.

## 3. FLEXIBLE OPERATION OF HIGH EFFICIENCY COAL POWER PLANTS TO ENSURE ADEQUATE POWER GRID STABILITY WHEN VARIABLE RENEWABLE ENERGY SOURCES ARE PART OF THE ENERGY MIX

As intermittent VRE sources such as solar and wind increase their share of grid-based power generation, the systems become increasingly unstable, Figure 4. In order to counter this, fossil fuel units are required to operate more frequently in cycling modes, compared to the baseload modes for which most were designed.

Coal power plant flexible operation, together with grid and demand side management, has become increasingly important for the integration of the intermittent energy sources on the grid to ensure adequate system stability (Henderson, 2014; Sloss, 2016). Without alternatives yet to be developed such as utility scale battery storage, this use of coal (or other fossil fuel) power sources is essential. Coal fired units are required to now achieve fast start-up, very low minimum load, rapid ramp rates and on/off cycling. Such operation at off-design conditions increases the wear and tear of plant components, which bring new challenges. Consequently, with the expectation of further introduction of intermittent VRE sources, new strategies and effective management continue to be required to mitigate and/or avoid a higher probability of equipment failure and consequent reduction in unit life, critical risk of process safety and increased costs (Hilleman 2018).

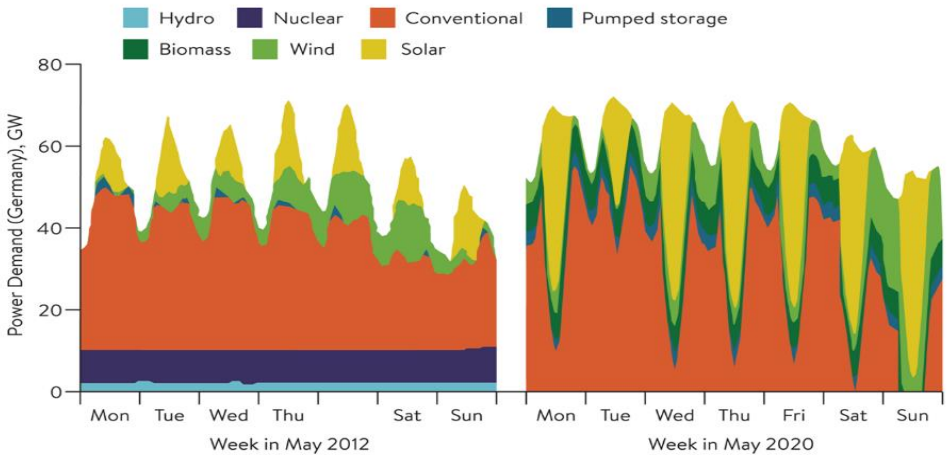



Figure 4 Estimated power demand in in Germany May 2012 and in May 2020

(Morris and others 2012)

Issues include thermal and mechanical fatigue stresses together with corrosion and differential expansion, often occurring in synergy, which can reduce the lifetime of certain components (Daury 2018; Henderson 2014). There are also adverse impacts on coal power performance. For example, a reduction in load leads to a corresponding heat rate reduction, which together with higher auxiliary power consumption leads to specific $CO_2$ emissions increasing.

For existing plants, there are several ways to improve flexibility (Henderson 2016). These include retrofitting new technology variants, either modifying existing or adopting new operating procedures, introducing awareness training for both operating and managerial level

personnel. Thus, different modes of cyclic operation of fossil plants and strategies for managing the negative impacts are identified. Options include new operating practices, use of advanced materials and installation of improved control systems. Such measures can improve heat rates and reduce the number of forced outages in existing fossil plants ((Henderson C 2014, Wiatros-Motyka M 2019). This section examines the various power plant systems where some form of upgrade is required together with a focussed consideration on the operational approach to optimise coal power plants for acceptable grid stability with associated coal power-based performance. It is complemented with the subsequent section that considers how the inclusion of significant coal (or gas) based dispatchable energy combined with CCS/CCUS to ensure very low carbon emissions may offer a cost effective and operationally sound approach to maintain flexible operation with ever lower $CO_2$ emissions.

### 3.1 Instrumentation and control

Optimisation of the instrumentation and control system is the most cost-effective way to improve plant flexibility and should be a precondition for other measures. Such modern control systems are vital for ensuring flexible power plant operation (Lockwood 2015), since they allow navigation between different loads and ensure stable operation by adjusting all related process variables, Figure 5. This improves accuracy, reliability and speed of change. In many plants, an upgrade of I&C is combined with plant engineering upgrades such as retrofits of the boiler, burners or turbine or other components (Agora Energiewende 2017).

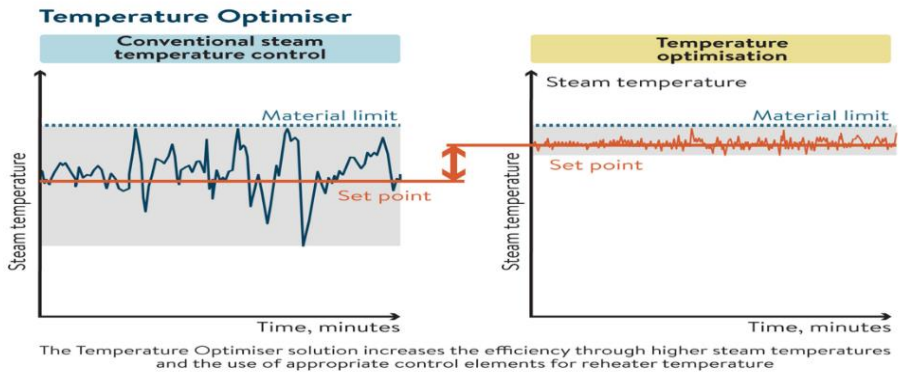



Figure 5 Example of temperature optimisation using Siemens SPPA-P3000 system (Chittora 2018)

### 3.2 Flexibility options

Operation with low minimum load limits the number of shutdowns required, which means less adverse impact on plant component life. There are several measures to achieve low minimum load, with stable combustion the key that is based on careful control of the boiler, fuel supply and combustion systems (Hamel and Nachtigall 2013).

Figure 6 MHPS Internally rifled evaporator tubes (Yamamoto and others, 2013)

Such measures include ensuring consistent coal quality and particle fineness, operation with low excess air, use of flame monitoring, fuel/ air flow control systems, tilting burners, auxiliary firing, operation with a lesser number of mills and only top-level burners, deploying smaller mills, thermal energy storage for feedwater heating, vertical internally rifled evaporators, Figure 6, plus sliding pressure operation and economiser modifications (IEA 2018). Currently, optimised coal-fired power plants can operate at less than 20% of full-load capacity (Schiffer 2015), with indications that levels as low as 10% can be achieved if various measures are implemented together.

Start-up procedures are complex as well as expensive since they usually require auxiliary fuel during the burners' ignition stage. Consequently, they should be avoided if possible, and if that is not achievable then the start-up time should be shortened in combination with a fast ramp-up. Such changes can be achieved through reliable ignition, integration of a gas turbine, reducing thickness of thick wall boiler components such as headers, including more headers, external heating of thick boiler components, and cleaning of boiler deposits (Martino 2013). Measures in the steam turbine include use of advanced seals, turbine bypass (HP or LP), and internal cooling of the turbine casing.

Many of the improvements for start-up aid high ramp up rates, which allow dynamic adjustment to achieve net power requirements, Figure 7. Additional measures include changing mill storage capacity, condensate throttling, and the use of an additional turbine valve. The ramp between partial load and full load for power plants involves load changes of approximately three percentage points per minute, and the change in mode of operation can therefore be achieved at all plants in less than half an hour.

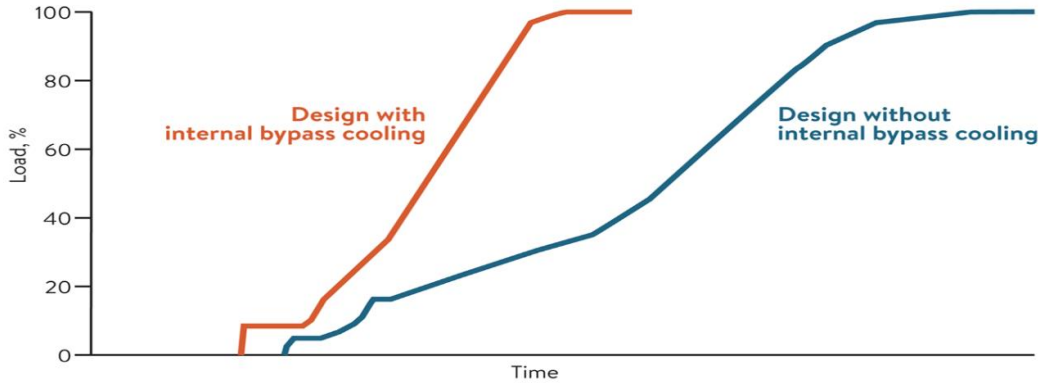



Figure 7 Ramp-up rates achieved with and without the internal bypass cooling (Chittora 2018)

Designers of new plants have an opportunity to include flexibility requirements at an early stage. For example, either use of new advanced materials for thick-wall high pressure components, such as headers, or designing them based on a shorter baseload operational life have been shown to reduce life consumption during rapid cycling. Designing plant for a sliding pressure operation is also effective. Additionally, plants which include a condensate throttling system can increase their primary frequency response significantly. Other design futures include steam cooling of the inner turbine casing as well as HP and feedwater heaters bypass and thermal energy storage for feedwater preheating.

### 3.3 Pollution control systems

The performance of some emission control systems can be affected by off-design conditions arising from the flexible operation of power plants since the temperature of the flue gas can change with the cycling regime. For example, the removal of particulate matter either with ESPs or fabric filters can accommodate rapid load changes provided that the temperature does not fall below the dew point (~90°C). At the latter condition, any moisture can lead to a build-up of dust, which can be difficult to remove (EPRI 2013). This can be countered with installation of a warming system to pre-heat the precipitators while the unit is being brought back on load. Generally, ESPs perform better at low loads because of the reduced proportion of unburnt carbon in ash and the increased residence time of the gases in the precipitator, which allows more of the dust to be collected.

In contrast, maintaining the temperature at the required level is essential to ensure effective NOx control (Zmuda R 2019; Boyle, Stamatakis and de Havilland 2015). For systems based on selective catalytic reduction (SCR), the inclusion of an additional flue gas heater prior to the SCR inlet has been used. For selective non- catalytic reduction systems, the use of a multiple zone injection approach, and the ability to bring injectors in and out of service as needed, allows for chemical release within the desired chemical and thermal environment (Davis, Rummenhohl, Benisvy and Schultz 2013).

For $SO_2$ removal with flue gas desulphurization, it is essential to minimize the number of shutdowns and start-ups to avoid slurry solidification and accumulation of start-up fuel oil residues on linings. It is normal practice to keep the FGD unit in stand-by mode when short outage periods occur. This avoids solid deposits and keeps the FGD unit ready for fast start-up.

There is a need for a more sophisticated control approach to meet these various conditions during cycling operation than is the case for NOx and PM controls.

### 3.4. Flexibility impact management

A high proportion of on-load failures originate from preventable damage caused during offload periods (Caravaagio 2014). The risks are higher for cycling units as frequent start-ups/shutdowns and standby periods disrupt the physical and chemical conditions within the water/steam circuit, leading to corrosion and other damage during standby. The resulting damage can be catastrophic; hence proper preservation of the all water-steam circuits is essential (McCann 2018).

Choosing the most applicable practices depends on site-specific factors, and the entire unit must be considered (EPRI 2014). Wet storage of the water systems and often the boiler is considered the most practical approach for cycling units, for which pH adjustment and elimination of oxygen are essential. This procedure includes complete deaeration of the condensate and feedwater and prevention of air entering the boiler and superheater. The latter can be achieved by nitrogen blanketing and/or maintaining boiler pressure. The pH adjustments for all the liquid, including condensed steam in the superheater, must be equal to or higher than normal pH conditions. The wet lay-up practices in all parts of the water/steam cycle can be enhanced using filming amines as a corrosion inhibitor, Figure 8. These are dosed to the entire circuit before the unit shutdown and their dosage needs to be controlled precisely (Moore 2018).

Figure 8 An example of amine coated turbine blades

(Image courtesy of Uniper)

The best method for preserving the reheater and steam turbine is dry storage. Residual heat of the turbine can typically maintain 'dry' conditions for 24-36 hours, but once a relative humidity either greater than 40% or equal to the 'dew point' temperature is reached, condensation and oxygen will initiate corrosion. Reheaters that are force-cooled require immediate purging of steam vapour as exclusion of oxygen laden air is difficult to achieve. Dry reheaters, like the turbine, are subject to condensation and aeration when cooling.

Monitoring of lay-up conditions is required to ensure the protective conditions are maintained (Matthews 2013).

### 3.5 Future considerations

The inclusion of intermittent VRE sources within a grid-based power generation system provides power with zero carbon dioxide emissions but this must be backed up with other sources to ensure adequate grid stability. In most instances, this is provided by coal fired power plants that can now operate in cycling modes with faster ramp rates, very low load and on/off operation (Reischke 2012). As the proportion of VRE increases on the grid, this need for dispatchable power from coal (and gas) fired units will become ever more critical (Kumar and Hillemann 2018), with the likelihood that further new strategies and effective management will be required to ensure that this operational approach can be achieved (VGB 2018). At the same time, such coal (and gas) fired plants emit significant quantities of $CO_2$. In the move towards a net zero carbon system, this can be countered through the inclusion of carbon capture and storage/utilisation (CCS/CCUS) on the fossil fuel power plants. The impact of such an inclusion is considered in the nest Section.

## 4 THE ROLE OF CCS/CCUS IN ENSURING COMPETITIVE NEAR ZERO CARBON DIOXIDE EMISSIONS WHILE MAINTAINING FLEXIBLE OPERATION AND ADEQUATE POWER GRID STABILITY WHEN VARIABLE RENEWABLE ENERGY SOURCES ARE PART OF THE ENERGY MIX

### 4.1 Limitations of a grid-based power system based on 100% variable renewable energy

Determining the optimum solution for a functioning and reliable power system under net-zero constraints is a complex problem. Reliable delivery of electricity to consumers throughout the year requires the system operator to instantaneously match supply and demand while maintaining grid frequency, voltage, and adequate inertia on the grid. In today's power systems, these functions are largely achieved using coal (or gas) thermal plant, which can quickly respond to unforeseen changes in either supply or demand, as well as inherently resist excursions in grid frequency through the inertia they provide. In contrast, although variable renewable energy (VRE) systems offer power with zero carbon dioxide input to the grid, they represent an intermittent option that without the contribution of dispatchable power from fossil fired plants will introduce instability into the grid operating system. This problem becomes ever more acute as the proportion of VRE is increases, Figure 9.

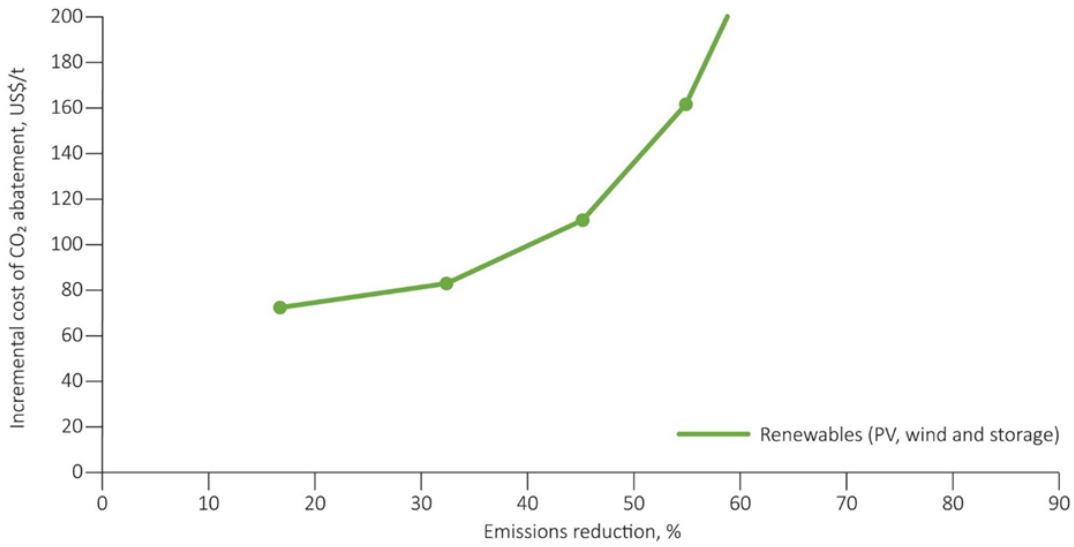


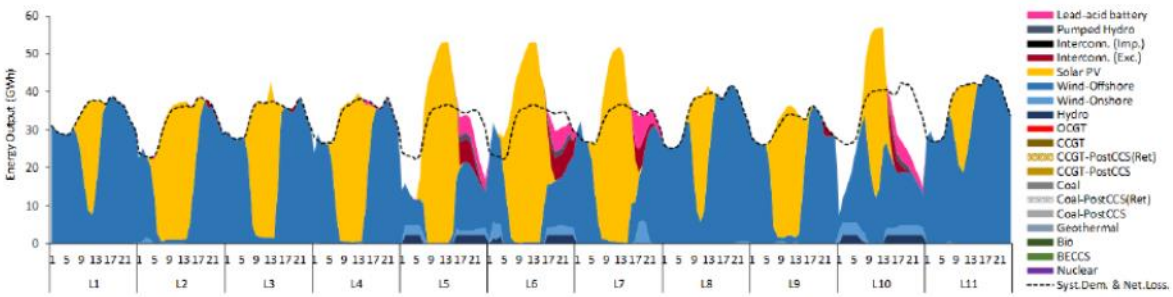

Figure 9 Analysis for Australia's National Electricity Market Grid (Boston and others 2018)

Consequently, despite many opinion formers suggesting that decarbonisation of both national and regional power systems could be achieved based almost entirely on generation from intermittent VRE sources, not only would this fail to achieve adequate stability, it would be a very high cost option.

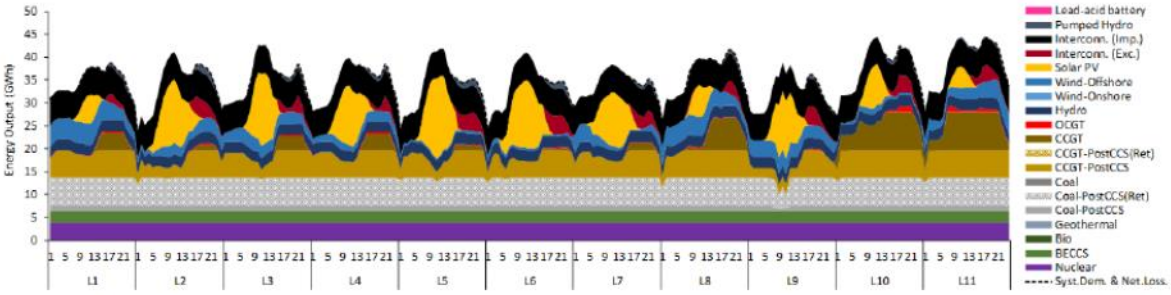
Nonetheless, coal power is not a low $CO_2$ emitter, and this too must be addressed, for which the use of $CO_2$ capture, transport and storage /utilisation (CCS/CCUS) offers a technically proven option with the key components having been proved at commercial scale. Unit costs for such a system are higher than wind and solar, which represent the lowest cost options for initial reductions in the $CO_2$ intensity of electricity production. However, strategies for achieving net-zero carbon power grids must consider the total system cost in order to provide a realistic path forward. As indicated below, greater decarbonisation of the grid will require input from flexible low-carbon generation such as CCS-equipped fossil fuel power plants.

### 4.2 The importance of total system cost analysis

Despite thermal plant equipped with CCS having a higher levelized cost of electricity than wind and solar power in most regions, the value of flexible, low-carbon generation increases as the proportion of renewables on the grid increases. At a certain level of system decarbonisation, it becomes cheaper to mitigate the next tonne of $CO_2$ using a CCS/CCUS thermal power plant, than by adding further wind or solar capacity.




Use of renewables and storage only, leading to periods of unmet demand




The lowest-cost mix with all technologies available

Figure 10 Projected net-zero electricity mixes for Poland in 2050, showing 11 representative days throughout the year (Pratama and Mac Dowell 2019)

This effect can be seen in the two scenarios for Poland as shown in Figure 10. The top dispatch curve shows a decarbonised grid using only renewables and battery storage, across 11 days representing different typical variations in weather and demand throughout the year. This shows that the role of batteries is limited by the need for periods of massive excess generation (in which the batteries can charge). There are several periods of unmet demand (blackouts) and high levels of curtailment (unused generation).

In contrast, the other dispatch curve shows the lowest-cost net-zero solution using all available technologies, including coal and gas power plant with CCS/CCUS and nuclear plant. Owing to the relative inflexibility of nuclear plant, the CCS-equipped thermal plants are used extensively for grid balancing. Not only does this electricity mix provide the required stability and flexibility, it has a total system cost that is only some 30% of that for the renewables-and storage only option.

In summary, in order to operate effectively and safely a power grid, while accommodating VRE sources, requires the inclusion of fossil energy thermal power plants, which in most locations will be a lower cost coal option than gas. With the inclusion of CCS/CCUS on the coal power plants, these units become very low carbon emitters (Budinas and others 2018). In the absence of such thermal power plants with their ability to introduce inertia into the grid, as the capacity of VRE sources is increased, the total system costs will increase significantly and in many cases the ability to meet full load demands will be compromised.

## 5. COAL-RENEWABLES INTEGRATION ON INDIVIDUAL POWER PLANTS

As considered in the previous sections, VRE has made a significant and challenging impact on established grid-based capacity. The intermittent nature of solar and wind power creates major instabilities on the grid, which will increase with all additional installation of these two technology options. As has been stated, there is an essential need for the inclusion of dispatchable power to provide the necessary system stability, which is currently provided by fossil energy power systems on a- round-the-clock basis, of which coal is the most used, reflecting its longstanding availability compared to, say, gas.

Nevertheless, given that a power generation site can accommodate more than one type of system, there may be merit in physically integrating solar options with individual coal fired power generation operations. The viability of any such coal-solar hybrids will depend on a combination of economic, environmental and political considerations, which will need to be evaluated on a case-by-case basis as designs are site-dependent (Mills 2017). The main applications are preheating of boiler feedwater, additional preheating of feedwater downstream from the top preheater, and the production of either intermediate pressure (IP) steam or main steam (Siros 2014; Roos 2015).

### 5.1 Coal-solar hybrid power plants

Of the two types of solar power currently available, that based on concentrated solar power (CSP) is in principle a viable option whereas integration using the photovoltaic system is incompatible. The CSP systems produce electricity directly from sunlight, using mirrors and lenses to gather and focus solar radiation into a concentrated beam that can be used as a heat source for a conventional thermal power plant. To put this in context, this hybrid technique is based on the physical linking of coal power plant with a solar power system in which these sources of energy are harnessed to create separate but parallel steam paths. These paths later converge to feed a shared steam-driven turbine and generate electricity as a combined force. This reduces the amount of steam extracted from the turbine, which can help improve cycle efficiency and reduce coal demand and/or increase the unit electrical output. With an increase in cycle efficiency this results in less $CO_2$ emissions per unit output.

A major advantage of CSP systems is that they can incorporate 'thermal storage' whereby excess heat that is collected during the day can be reclaimed later (at night) and used to raise steam. Although not considered a true dispatchable system since reclaiming stored heat does not yet lead to 24 hours operation, this approach would mean that there is more inertia in the system, which helps limit fluctuations in the grid output. CSP plants need to be of utility scale to be economically viable and at present their global capacity deployment is a small fraction of that provided by photovoltaic systems. If stand-alone, they need the associated infrastructure such as steam turbines and grid connection, which can be an expensive commitment for their usual scale of generation. However, if integrated into an existing coal power plant, much of this infrastructure is already available, greatly reducing investment costs. As such, incorporating solar energy in these ways will cost less than an equivalent stand-alone CSP plant. The LCOE from a coal-solar hybrid will be lower than that of a stand-alone CSP plant, and it has been suggested that it could compete with that produced by PV systems (Siros 2014). However, recent reductions in costs for the latter technology may well mean that it now has a competitive financial edge, albeit without the dispatchable advantages. During daylight operation, CSP can be used to reduce coal consumption (coal reducing mode). As the radiation decreases during the latter part of the day, the coal contribution can be increased, allowing the plant's boiler to

always operate at full load. Alternatively, input from the solar field can be used to produce additional steam that is then fed through the steam turbine, increasing electricity output (solar boost). As both are dependent on the availability of sunlight, output from a hybrid operating in solar boost mode can be as variable as PV. However, when in coal saving mode, electricity is dispatchable. Thus, the system regulator can rely on power being available. Whichever mode is adopted, the design and integration of the solar field into the conventional system is critical for the proper functioning of a hybrid plant. In principle, this form of hybrid technology can be applied to any form of conventional thermal (coal, gas, oil or biomass-fired) power plant, either existing or new build, Figure 11.

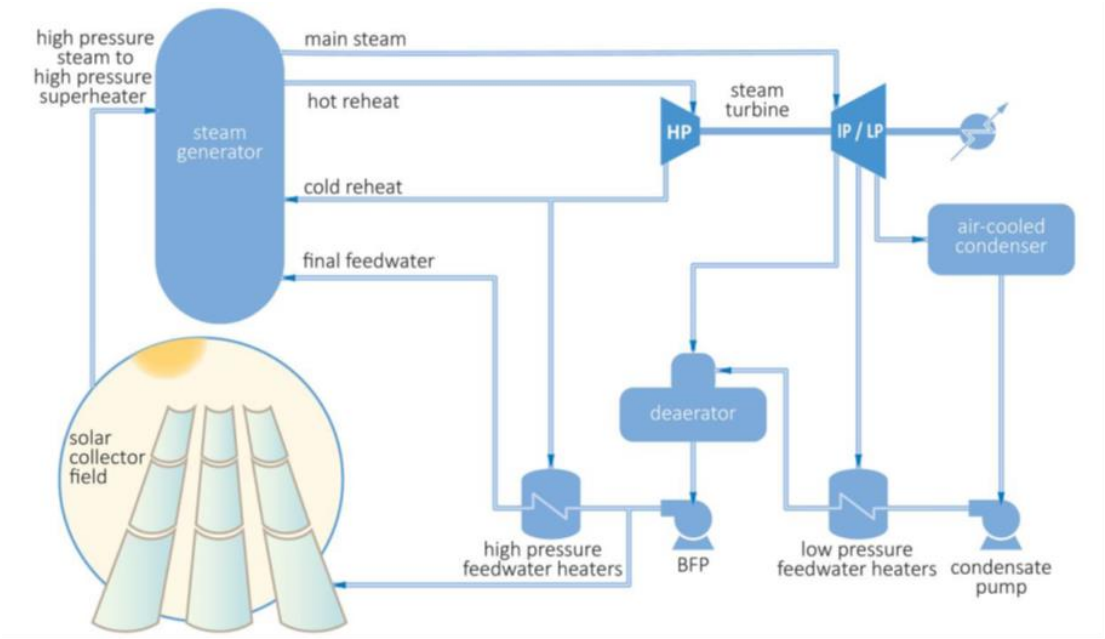



Figure 11 Generating high pressure steam using solar power

### 5.2 Prospects for coal-solar hybridisation

The primary advantages cited for coal-solar hybridisation (EPRI 2010b; Rajpaul 2014; Roos 2015; Appleyard 2015; IT Power 2012) are:

- solar thermal augmentation can reduce coal demand, reducing plant emissions and fuel costs per MWh generated;
- hybridisation will reduce the level of coal and ash handling, reducing load on components such as fabric filters, pulverising mills, and ash crushers
- the lifespan of existing thermal facilities could be extended, where for example, regulatory changes require a coal-fired plant to reduce emissions or face closure
- the higher initial investment is balanced either by reduced fossil fuel consumption or increased power output
- both base load and near- dispatchable power peaking and can be provided to the grid
- the combined technology could help meet renewable portfolio standards and $CO_2$ emissions reduction goals at a lower capital cost than deployment of stand-alone solar plants. Capex is less for the same capacity

- project development timelines, transmission and interconnection costs can all be reduced in due course through learning by doing
- similarly, the ongoing technology development will lead to further cost reductions for CSP components

However, these potential advantages have not been realised. There have been many techno-economic studies undertaken and various component development options identified to improve coal-solar hybrid power systems. Countries that have shown interest include USA, Australia, Chile, Macedonia, South Africa, China, India and Zimbabwe (Mills 2017). However, there have been few plants deployed so far. Over the last decade, several coal-solar hybrids have been developed in the USA, of which the Cameo Demonstration Project was the first to successfully use solar energy to heat boiler feedwater, thereby reducing coal consumption and plant emissions but it didn't lead to larger scale deployment.

Figure 12 Abengoa Solar sun-tracking parabolic trough technology at Cameo Generating Station (photograph courtesy of Xcel Energy)

The world's first coal-solar hybrid power plant demonstration, namely the Cameo Generating Station, Colorado Integrated Solar Project, USA, was a part of the State's Innovative Clean Technology Program. It was designed to test promising new technologies that had the potential to reduce greenhouse gas emissions and produce other environmental improvements. The Cameo coal power plant comprised two 49 MWe coal-fired units. The solar component comprised a 2 MWe sun-tracking parabolic trough technology to supplement the use of coal, Figure 12. This included a 2.6 hectare solar field housing eight rows of 150m long solar troughs. The heat generated was focused on a heat exchanger where it was used to preheat feedwater supplied to Unit 2 of the Cameo plant (Mills 2011).

In 2010, the 7-month pilot/demonstration programme was implemented, after which the station was retired and the CSP plant decommissioned. The hybrid system confirmed that this type of supplemental application to an existing fossil fuel-fired boiler was feasible and would not impact adversely on normal generation operations. The addition of solar energy increased overall plant efficiency by some 1%, while coal demand and air emissions were reduced (~600 $tCO_2$, >900 kg NOx, and 2450 kg $SO_2$) over the lifetime of the testing. Unit availability was 98.4%. The only

downside was the power needed for operation of the CSP system, which was ~0.4% of the equivalent kWh output.

Integration and operation of the CSP system with the existing coal-fired unit was deemed a success; however, the situation regarding costs and efficiencies was less clear. For a cost of US$4.5 million, the hybrid plant produced the equivalent of 1MW from solar power out of the total output of 49 MW. Consequently, the plant operator felt unable to make any definitive recommendations regarding further future deployment at any of its other power plants (Public Service Company of Colorado, 2011). No plans have been announced for any further coal-solar hybrids in the immediate future.

### 5.3 Future opportunities

There has been a lot of studies but limited evidence of a fully successful practical application. Consequently, while the coal-solar hybrid approach can be established, it is questionable whether this will be a cost-effective option. This is due partly to the limitation imposed by the need for adequate solar radiation that restricts the technology to certain regions. Also needed in those localities is a coal supply and a coal-fired power plant suitable for retrofitting. Such opportunities may be limited to niche applications where the conditions are right and there is a local need for electricity. As such, widespread uptake of the technology appears unlikely.

## 6. COAL-GAS COFIRING ON INDIVIDUAL POWER PLANTS

Cofiring in this context refers to the regular use of gas as a secondary fuel rather than just using small amounts for start-up and warming operations. The market drivers for moving to this alternative firing mode are multi-factored although in part environmentally driven. Cofiring gas in coal-fired power plants can reduce emissions, improve operational flexibility, and allow faster, cleaner start-ups, Table 5.

Table 5 Possible reasons for cofiring coal and natural gas in power plants (Mills 2017)

| |
|---|
| Environmental mitigation of $CO_2$ emissions from coal-fired boilers |
| Reducing emissions of $SO_2$, NOx and particulates |
| Providing a mechanism for generation and sale of cost-effective, dispatchable electricity |
| Public acceptance |
| Economic Maintenance of a coal supply sector and employment |
| May be the least-cost way for coal-burning utilities to improve fuel flexibility |
| Offers potential financial advantageous in competitive markets through fuel diversity |
| Could support companies to get credits for early voluntary greenhouse gas abatement measures |

### 6.1 Market drivers

The environmental advantages arise through simultaneously replacing some of the coal feed with gas, which will equate to lower emissions, an important factor in meeting environmental legislation. At the same time, this will reduce the load on control systems; for instance, less FGD reagents will be consumed, SCR catalyst lifetime can be extended, and particulate collection systems will require less frequent cleaning. Replacement of 35% of coal feed with gas using a tailored cofiring system can reduce $SO_2$/$SO_3$ emissions by up to 35%, NOx emissions by 45%,

particulates by 35%, mercury by 35%, and $CO_2$ by 20% (Breen Energy Solutions 2014). This results in lower O&M costs on these environmental control systems. Stable low load operation, which is readily achieved on coal-only power plants (Section 2), can also be maintained. While plants currently operate at a fixed coal: gas ratio, there is scope to engineer systems whereby that ratio can be changed, providing a degree of flexibility in terms of fuel supply.

Cofiring also can offer other cost savings since it may allow switching to a cheaper coal source. For example, in the USA, a power plant might change from higher grade bituminous coal to subbituminous supplies, while introducing a gas burn to maintain plant capacity. That said, even slight changes in fuel price ratio between coal and gas can result in significant swings in production costs, and this can create market opportunities for utilities that have both gas- and coal-fired assets. Equally important, adding gas to coal-fired plants offers utilities the possibility of a rapid response to changes in load demand and deep cycling capability (Cassell 2016). A power plant that can cycle quickly to meet peaks and troughs in demand is more likely to be profitable even though significant equipment modifications may be required to retrofit a coal fired power plant (see below).

From a cofiring cost versus benefits perspective, a key requirement is that the coal-fired plant has an adequate source of natural gas available at an acceptable price. If the plant already uses gas for warm-up operations, existing infrastructure may be adequate. If not, additional supply and control equipment may be required. A major attraction often cited for cofiring is the low price of natural gas. Although this is currently the case in the USA, gas is more expensive and less readily available in other countries. Even in the USA, there are concerns that gas prices could increase significantly in the future since political and environmental pressures on hydraulic fracturing and investments for gas export facilities could drive the price of natural gas upwards (R-V Industries, 2016).

### 6.2 Technology development issues

In order to establish a retrofit cofiring capacity, there are several technical challenges to be addressed, which include changes to control systems and plant hardware for the coal fired plant. The costs involved need to be balanced against the flexibility benefits, as noted above. Thus:

- The combustion and heat transfer characteristics of coal and gas flames are different, and this can lead to heat transfer imbalances throughout the steam generator, with a need for re-engineering to accommodate the complete spectrum of load dispatch and cycling scenarios (Gossard 2015).
- The high hydrogen content of natural gas (~25% mass) means that latent heat losses resulting from the production of water during the combustion process can be much higher than for all but the wettest coals;
- Performance can be sensitive to natural gas burner placement, which can require careful adjustment to avoid excessive temperatures or incomplete combustion in certain areas (Reinhart and others 2012).

The possible ways to reconfigure an existing coal fired unit for gas cofiring depend on the degree of flexibility required. The simplest option is to retrofit existing oil-fired ignitors with natural gas equivalents, which typically allows for a maximum gas firing capability of 10–20%. If the unit is equipped with oil-fired warm-up guns, these too can be replaced with natural gas-fired units, which increases potential natural gas firing capability to some 30–50%. Should a greater level

still be required, gas firing needs to be incorporated into the main burner system (Reinhart and others, 2012). This entails modifications such as the installation of gas rings around the existing coal burners, installation of gas spuds in the annulus or centre of the burner. The most expensive option for cofiring is the addition of full-sized natural gas burners or the replacement of the existing coal burners with gas or dual-fuel units. Changes to the combustion control system are likely to be required.

For NOx control, natural gas is a common reburn fuel as it is easy to inject and control and does not contain any fuel-nitrogen. It can reduce NOx emissions by up to 70%. It is a three-stage combustion process that takes place in the primary, reburn and burnout zones. In the primary zone, pulverised coal is fired through conventional or low-NOx burners operating at low excess air. A second fuel injection is made in a region of the boiler after the coal combustion, creating a fuel-rich reaction zone (the reburn zone). Here reactive radical species are produced from the natural gas that react chemically with the NOx produced in the primary zone, reducing it to molecular nitrogen. The partial combustion of the natural gas in this reburn zone results in high levels of CO. A final addition of overfire air, creating the burnout zone, completes the overall combustion process. Consequently, reburning systems can provide a means for incorporating a sizeable amount of natural gas into an existing coal-fired power plant.

While natural gas is a common option for cofiring with coal, there are others. If adequate supplies are available within an acceptable distance such that transport costs are not prohibitive, any of the following options could potentially be used for cofiring:

- Conventional pipeline natural gas
- Shale gas
- Liquefied natural gas
- Landfill gas
- Coalbed methane and coal mine methane
- Output from an underground coal gasification process

### 6.3 Current situation and market prospects for cofiring deployment

Worldwide, there are various countries that operate coal fired power plants with a gas supply that they use regularly as part of their operational approach. The more significant countries in terms of coal fired capacity with cofired gas are listed in Table 6. Many other countries operate more modest numbers of coal-fired plants with the potential for cofiring. These include selected plants in Australia, Kyrgyzstan, Poland, Slovakia, Bulgaria, and Thailand.

Table 6 Larger fleets of coal-fired power plants that also use natural gas

(Platts, 2017)

| Country | Capacity (MW) | Main fuel type(s) | Power plant types |
|---|---|---|---|
| USA | 27071 | bituminous, subbituminous, lignite | subcritical, supercritical |
| Ukraine | 20740 | bituminous, subbituminous | subcritical, supercritical |
| Russia | 12396 | bituminous, subbituminous, lignite | subcritical, supercritical |

| | | | |
|---|---|---|---|
| Romania | 3525 | bituminous, lignite | subcritical |
| Germany | 3508 | bituminous, lignite | subcritical, supercritical |
| Indonesia | 3400 | subbituminous | Subcritical |
| China | 3175 | bituminous, subbituminous, lignite | subcritical, supercritical |
| Netherlands | 2360 | bituminous | subcritical, supercritical |
| Uzbekistan | 2100 | lignite | subcritical, supercritical |
| Turkey | 1600 | bituminous | subcritical, supercritical |
| Malaysia | 1600 | bituminous | subcritical |
| Moldova | 1600 | bituminous | subcritical |
| Italy | 1465 | bituminous | subcritical, |
| India | 1400 | bituminous | subcritical |
| Israel | 1150 | bituminous | subcritical |
| Czech Republic | 1115 | bituminous, lignite | subcritical |

The overriding factor is the price and availability of gas since in some regions, although affordable for limited application, gas is too expensive for bulk use. Furthermore, in some countries, exporting natural gas is a more lucrative option than using it in their power plants such that exports take priority over domestic use. To put this in perspective, for some years, gas prices in the USA have been at historically low levels, typically less than US$5.0/1000 MJ and below US$2.4/1000MJ in 2015. In contrast, also in 2015, prices in, for example, Ukraine, were US$9.0/1000MJ and in China, they were about US$9.2/1000MJ, with higher prices in South Korea, Japan and Taiwan, countries that rely heavily on imported supplies of LNG.

National and regional examples of the work undertaken for cofiring introduction are set out below.

**6.3.1 USA**

The biggest potential near-term market for cofiring is in the USA. Shale gas is a low-cost benefit that is almost unique to the USA, which has transformed both its domestic energy use options and international sales opportunities. There is a near-term market desire to introduce gas cofiring to extend the working lives of coal fired plants whilst simultaneously reducing their environmental footprint (Silverstein 2016). However, the degree of uncertainty that remains over future government policies and the environmental landscape means that many utilities are reluctant to significantly invest in their coal-fired facilities since likely returns on investment do not look attractive (Volcovici 2015). At the same time, since many US power plants have moved away from steady-state base load operation to frequent cycling and load following, there are more periods of low load and plant start-ups, which increase the amount of start-up fuel burned. Consequently, use of gas is not necessarily as a main fuel but rather as a switch from fuel oil during periods of start-up, which is a relatively low risk way forward.

Some US coal plants can accommodate higher levels of cofiring gas. An industry survey identified nearly 200 individual plants with a combined capacity of ~78.5 GW that had the capability of

cofiring at a significant level. These were units that had fired coal and gas together for electricity generation during at least one month in the previous years. During the period 2008-11, the volume of gas burned by these plants increased by 11% whilst the amount of coal burned fell 9% (Hameed, 2012).

An interesting approach has been taken forward in Florida, at the Orlando Utilities Commission (OUC), which has converted two 450 MW coal-fired units at its Stanton Energy Center to cofire natural gas as a means of increasing fuel diversity while dealing with increased cycling (Reinhart and others 2012). A key element of the switch to cofiring has involved equipping the two coal-fired boilers with igniter systems that can accommodate various fuel firing configurations. As well as cofiring natural gas, both units can also cofire landfill gas. This provides up to 22 MW of additional power, enough to displace up to 3% of the coal consumed by the boilers. Landfill gas is cofired with coal in both full and low load operations. In addition, in order to capitalise on low natural gas prices, Units 1 and 2 can operate with the gas igniters in continual full-time service (Parent and Czarniecki 2016).

While much of the focus on cofiring has been on older coal-fired plants, it is also seen as an option for some newer more advanced units. This has included the 700 MW supercritical Longview pulverised coal fired power plant in West Virginia, considered to be one of the most efficient in the USA (Modern Power Systems 2016). Longview has taken advantage of historically low natural gas prices by cofiring up to 20% of unit heat input. No additional investment was needed to achieve this. Coal burned is run-of-mine, used without preparation (Modern Power Systems, 2016). In addition, the plant made use of a large capacity mobile LNG facility, installed to ensure that gas supply remained available for start-up and significant load changes when pipeline natural gas supplies might be curtailed, for example, during cold weather, when residential and key industrial users took precedence.

For the future, industry opinion is that operating advantages are likely to go to utilities with diversified fleets, such as those with the ability to switch between fuels (Nowling 2015).

### 6.3.2 Asia Pacific region

In the Asia-Pacific region, various coal-fired power plants report natural gas as an 'alternative' fuel, although most rely mainly on coal. However, there are a number that have the capability of cofiring natural gas and do so on a regular basis. For example, there are major plants in Indonesia, Malaysia, Thailand and in several parts of India and China. These include the newest unit of the 4 GW Suralaya power plant on the island of Java, which is Indonesia's largest coal-fired power plant and uses subbituminous coal as its main source of fuel (Figure 13). This fuel-flexible unit was built with the capability of also cofiring differing amounts of pipeline natural gas or LNG, as well as fuel oil or biomass.

Figure 13 The Suralaya plant in Indonesia (photograph courtesy of Indonesia Power)

#### 6.3.3 Europe and Eurasia

The situation is similar in parts of Europe to that in the Asia Pacific region, although coal-fired plants normally use only modest amounts of gas. Countries where this mode of operation prevails include The Netherlands, Romania, Germany, the Czech Republic, Austria, Slovakia, Poland, Italy, Moldova, Bulgaria, Turkey and Spain. Several power plants within Russia and some of the former Soviet Union states such as Uzbekistan also operate in a similar manner (Table 6).

#### 6.3.4 Middle East

A major construction project is underway in Dubai, where the Hassyan power plant is under construction for the state-owned Dubai Electricity and Water Authority (DEWA). This 2.4 GW USC plant has been designed to be capable of operating on either 100% coal or gas, or combinations of both. Construction began in November 2016 and the plant is expected to be fully operational by 2023 (DEWA 2017). Subsequently, DEWA plans to launch two additional projects, to bring the total capacity to 3.6 GW.

A consortium comprising ACWA Power and Harbin Electric is currently building the (4 x 600 MW) coal-fired plant. The project is being supported by a 25-year power purchase agreement (PPA) with DEWA, which includes provision for a 25-year secure delivery of coal to the plant. The new plant will meet emission limits that are stricter than those specified in the EU Industrial Emissions Directive, and it is intended to contribute to the Dubai Clean Energy Strategy 2050, which aims to generate 7% of the country's electricity from clean coal by 2030.

In normal operation, natural gas only will be used during start-up, shut down, and for flame stabilisation, and with coal throughout the operational range of the boiler (Grant, 2017). It will be supplied from the United Arab Emirates (UAE) gas network. The UAE is a gas producer, although it is a net importer of gas for power generation.

### 6.4 The way forward

To date, co firing of coal and gas, beyond the latter fuel's restricted use for start-ups, and plant warming operations, appears to have a niche role on a global basis. There are several plants established in the USA, with others in the process of being converted, which is due to reliable

affordable supplies of natural gas that can help coal fired power plant operators meet tightening environmental standards. Cofiring offers possible benefits to at least some coal-fired plants where cost savings can be made through the ability to switch between whichever fuel is cheapest at the time. For the USA, most opportunities will be for retrofits and upgrading of existing plants, which will require modifications of burners and in some changes to heat transfer components to best accommodate the different characteristics of coal and gas combustion Given the wide range of designs for existing power plants, such cofiring projects need to be evaluated on a case-by-case basis to ensure that the various economic, operational and environmental factors are fully considered. In contrast, for new cofiring plants, such concerns can be accommodated at the design stage.

Elsewhere, opportunities appear to be limited due primarily to limits on availability of a reliable supply of gas at a suitable price although the USC plant being constructed in Dubai by DEWA is an excellent example of what can be achieved to deliver flexible and reliable power with the added security of supply provided by having both coal and gas available.

However, while the ongoing development of the current tranche of cofired plants could well lead to greater confidence in further deployment of the technology, with other options available it may struggle to gain significant additional market share.

# 7 COFIRING COAL WITH BIOMASS AND VARIOUS ORGANIC WASTES

## 7.1 Background

Sustainably sourced biomass is considered to be carbon neutral in that the $CO_2$ released during its combustion will subsequently be absorbed by further biomass sources such that the net $CO_2$ release is close to zero (IEA-ETSAP 2013; IHI 2017). At the same time, typical biomass-only fired power plants have small capacity and modest operating efficiencies, often with relatively high conventional pollutant emissions ($SO_2$, NOx, particulates). In contrast, cofiring biomass (and various organic wastes) with coal in modern, large coal-fired power plants can achieve a higher efficiency and better environmental performance than these smaller 100% biomass-fired power plants, while the incremental investment for cofiring is significantly lower than the cost of dedicated biomass power. A disadvantage is that most biomass, apart from waste-derived fuels, has a higher price per tonne at the power plant gate than the equivalent coal (Dooley and Mason 2018). Other possible drawbacks of cofiring include biomass transportation and handling, fuel conversion, loss of boiler efficiency, need to counter slagging, fouling, corrosion, and limits on ash utilisation. These drawbacks and the associated extra costs mean that cofiring biomass in the coal power sector is only seen to be worthwhile by its stakeholders if some form of governmental support is made available, such as positive policies or direct finance to encourage reduction in $CO_2$ emissions (Minchener 2017; Canadian Clean Power Coalition 2017).

## 7.2 Technology deployment issues

The European Union (EU) has been the world leader with more than 20 years' deployment experience for the cofiring of biomass with coal (European Biomass Industry Association). In most cases the biomass comprises wood pellets that have been produced from offcuts arising from logging operations in North America and then shipped to Europe (Zhang 2019). Some countries, such as Denmark, the Netherlands, Poland and the UK, where intensive cofiring activity has taken place, have developed a wide range of support mechanisms (Carbo and others

2017). These include feed in tariffs (FITs), which are price based and generally use administratively set prices to compensate renewable energy generators. Others include renewable portfolio standards (RPS) that are quantity based and promote cofiring in a cost-effective manner. In contrast, other incentives, such as carbon taxes, have been too low to incentivise the adoption of biomass cofiring.

Within the EU, others, such as Finland, France, Germany, and Italy, do not have support schemes for cofiring but have some cofiring activity.

From a regional perspective, within the next decade, many Western European countries plan to phase out coal, which means that cofiring will decline too, either closed with the coal-fired power plants or replaced by 100% biomass conversion, possibly in what were the large coal fired units. However, cofiring has fulfilled an important transitional role in decarbonisation and extending the lives of some coal-fired power plants. The drivers to introduce cofiring have moved from the EU to other OECD countries and to developing nations in Asia. Many countries, such as China, India, Japan, Malaysia, South Korea, and Vietnam have active cofiring projects. For example, cofiring is expanding rapidly in Japan and South Korea due to strong supportive policies (Aikawa 2017; Kwon 2016). However, some management and technical issues have been raised and biomass sustainability is the main concern for these two countries. The Japanese Feed-in Tariff (FIT) scheme does not offer an additional incentive for combined heat and power (CHP) plants to use the heat and does not support existing plants. However, some older Japanese coal-fired power plants are still adopting cofiring technology as it offers a means of achieving the 44.3% electricity efficiency standard required by March 2031. That said, Japan has some twenty cofiring projects firing coal with wood pellets both in the power and the large industrial process sectors (MHPS 2018; Chubu Electric Power Co 2017). In South Korea, cofiring is supported by the 2012 Renewable Portfolio Standard and more than 90% of the wood pellets used are imported since domestic production cannot meet the demand. Following a review (Yun and Jung 2017), the South Korean government reduced the renewable energy credit weightings for biomass cofiring in May 2018. This may ultimately have a negative impact, as without certain levels of subsidies the cost of biomass cofiring might become too high for the utilities to maintain operations.

Figure 14 China's first biomass cofiring pilot project at Xiangyang coal-fired power station (photograph courtesy of China Hefei Debo Bioenergy Ltd)

In some developing countries there are differences from the OECD practices. Thus, China is starting to cofire local agricultural and forestry wastes and sludge. As well contributing in part to decarbonisation of its coal power fleet, this approach prevents indiscriminate burning of such waste materials thereby greatly improving local air quality. It has planned 89 pilot demonstration projects (China NEA 2017), one of which started operation in September 2018, see Figure 14. However, China still does not have an adequate supportive mechanism in place to ensure a smooth deployment of cofiring (Li 2018).

In contrast, cofiring has never fully developed in the USA and Canada due to the lack of supportive policies. This is despite the massive forestry resource, abundant supply of wood pellets, currently designated solely for export, and an old coal-fired fleet. Similarly, although longstanding coal users, neither Australia nor South Africa are active in cofiring biomass with coal because of a lack of support mechanisms. Australia has great potential to grow biomass and has vast resources of agricultural and forestry wastes. In contrast, South Africa's domestic biomass resources are limited since water scarcity and food supply constraints make the country less suitable to develop bioenergy.

### 7.3 Future prospects

Cofiring carbon neutral biomass and other organic wastes with coal to reduce $CO_2$ emissions can contribute towards a net-zero carbon power sector. It also offers a route to use agricultural wastes such as rice husks and straw, which otherwise tend to be burned indiscriminately in the fields resulting in very significant air pollution. However, although it is a relatively low-cost technical route to partially decarbonise a coal fleet with associated air quality improvements, government supportive regulatory policies and financial subsidies are needed to make high ratio cofiring a viable proposition. Currently, this technology migration to Asia offers significant potential in the near term provided that adequate subsidies can be established.

## 8. THE WAY FORWARD THROUGH SUCCESSFUL INTERPLAY OF TECHNOLOGIES

Energy demand continues to increase while electricity remains a key component in such a mix. The generation of electricity can be achieved with many fuel sources such as coal, gas and biomass, which will be dispatchable while those obtained from wind or solar are intermittent variable energy sources. Despite many governments and organisations pledging to establish net zero carbon neutral systems by 2050, based on VRE sources, the reality is rather different.

A robust, effective power generation grid system needs to include dispatchable power. This refers to sources of electricity that can be used on demand and dispatched at the request of power grid operators, according to market needs. Dispatchable generators can either be turned on or off and can adjust their power output according to requirements. Sources include coal, gas and biomass. In contrast VRE sources are variable and intermittent. Currently, without support from dispatchable sources, grids based on VRE would be unstable and not capable of effective operation, being prone to sudden increases or losses of output, leading to blackouts under many conditions.

There has been considerable development of coal fired power plant designs so that they can meet previously unprecedented low load conditions, very fast ramp up and down while maintaining overall environmental performance. Through these efforts, the interplay of these coal based and VRE technologies can achieve an acceptable operational performance that meets the grid-based standards.

In order to take things further, there is a need to reduce the $CO_2$ emissions from the coal (and gas) plants as a key step towards carbon neutrality. This can be achieved through the inclusion of CCS/CCUS, which can reduce $CO_2$ emissions to well below 10%. Establishing CCS/CCUS is currently seen as expensive relative to the introduction of VRE sources that have low unit costs on a LCOE basis. However, as the proportion of VRE sources increases, the total system costs increase rapidly to the point where the inclusion of CCS/CCUS is seen as a more attractive option. There is growing evidence that not only does the interplay of coal with CCS/CCUS together with VRE result in lower total system costs, it also can ensure all system demand profiles can be achieved, unlike the case where VRE only is considered.

Consequently, there is an overwhelming need to support coal (or gas) with CCS/CCUS as a low carbon option for the interplay with VRE sources on the grid. Any major projects of this type need to be positively supported by high profile champions both to ensure government support but also to maintain momentum and interest with the general public. They need to present a compelling vision of the key role that CCS/CCUS needs to fill in ensuring a successful move towards carbon neutrality. This must include building the global case for CCS/CCUS so that it is positively included and acted upon as part of national agendas.

This interplay between dispatchable power and VRE sources is the key issue to be considered. There are other opportunities, in this case for integration of VRE sources with individual coal fired power plants. These approaches are technically adequate and allow the full range of the power plant's operating range to be achieved. The use of concentrated solar power provides scope to produce additional steam that can either boost power production (solar boost) or can be used to reduce coal use (coal reducing mode). However, under current market conditions they tend not to offer large scale and geographically diverse deployment opportunities and to date take-up of the technology has been limited.

Similarly, gas can be cofired in coal power plants  and this has positive benefits, including lower conventional emissions. However, as with the previous option, the benefits do not necessarily justify the investment costs and again technology take-up is limited.

Finally, the cofiring of coal with sustainable biomass offers an alternative way forward. This can provide a relatively small reduction in $CO_2$ emissions as the usual option is to limit the renewable energy input thereby avoiding major power plant modifications. However, in developing countries that renewable input can comprise agricultural residues that otherwise would most likely be burnt indiscriminately in the fields. As such, it provides a means to eliminate renewable energy induced air quality problems, which has significant attractions. That said, it is a technology variant that will require some level of subsidy since sustainable biomass tends to be more expensive than coal. In those countries where coal use is the preferred option and there are supplies of biomass available, this variant seems likely to prove attractive.

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