Review Article

Combining solar power with coal-fired power plants, or cofiring natural gas

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Abstract

Coal-fired power operators continue to look for ways to increase the efficiency and extend the working lives of their plants by improving operational flexibility and reducing environmental impact. Two possible options are explored here: combining solar energy with coal-fired power generation, and cofiring natural gas in coal-fired plants. Both techniques show potential. Depending on the individual circumstances, both can increase the flexibility of a power plant whilst reducing its emissions. In some cases, plant costs could also be reduced. Clearly, any solar-based system is limited geographically to locations that receive consistently high levels of solar radiation. Similarly, although many coal-fired plants already burn limited amounts of gas alongside their coal feed, for cofiring at a significant level, a reliable, affordable supply of natural gas is needed. This is not the case everywhere. But for each technology, there are niche and mainstream locations where the criteria can be met. The need for good solar radiation means that the uptake of coal-solar hybrids will be limited. Cofiring natural gas has wider potential: currently, the largest near-term market appears to be for application to existing coal-fired plants in the USA. However, where gas is available and affordable, potential markets also exist in some other countries.

Key words: coal-fired power plant; coal-solar hybrid; power generation; solar power; cofiring; hybrid

Introduction

Around the world, interest is growing in the sustainable provision of reliable, low-cost sources of energy. Increasingly, this has prompted utilities to examine alternatives to the fossil fuels that have traditionally provided the bulk of their electricity output. However, many developed and emerging economies continue to rely on coal for much of their electricity. In some, coal-fired power production is operating in an increasingly uncertain marketplace and faces intense competition from other forms of generation such as natural gas, nuclear and renewables. Set against this background, operators of coal-fired plants continue to look for ways to increase the efficiency and extend the working lives of their plants, often by improving operational flexibility and reducing environmental impact [1].

There are various ways that this might be achieved, two of which are explored in this article: combining solar energy with coal-fired power generation and cofiring natural gas in coal-fired power plants. The pairing of coal and solar energy may seem an unlikely combination, but under the appropriate circumstances, could offer an elegant solution to combining the reliability and cost-effectiveness of large-scale coal-fired generation with an emissions-free form of renewable energy. Coal and natural gas seem a more ‘natural’ partnership, and again, there is potential for some coal-fired plants to enhance their flexibility and improve their performance.
Fossil fuels such as coal and gas are still vitally important in generating much of the world’s electricity, continuing to provide reliable, low-cost supplies. Electricity generated by renewables such as wind and solar is more expensive. Renewables are often heavily subsidized, with costs passed on to the end-user. The other major drawback is that most are weather dependent. Hence output is intermittent and can vary widely and in a short space of time [2]. Consequently, other generation systems (such as coal- and gas-fired plants) are needed to provide backup when supply is inadequate or unavailable. Based on data from 26 OECD countries (1993–2013) an estimated 8 MW of backup capacity is required for each 10 MW of intermittent renewables capacity added to a system [3, 4].

Despite these reservations, there are clear incentives to explore options for combining renewables with conventional thermal power plants so that each provides advantages to the other, in the process, creating a cleaner, more efficient generating system. One possible option is to combine solar thermal power with coal-fired generating capacity—so-called coal-solar hybridization.

1 Coal-solar hybrids

The media sometimes reports on the development of ‘hybrid’ power projects, although in reality these are often merely co-located generation facilities. For example, photovoltaic (PV) solar cells might be added to a combined-cycle gas turbine (CCGT) plant. Clearly, these solar assets generate electricity, but this is fed into the grid independently of the gas-fired plant. Under this type of arrangement, the solar facility may serve to diversify the economic interests of the plant’s owner or reduce the overall environmental footprint of the site, but the PV and CCGT are not as tightly integrated as they might first appear. India plans to install a significant amount of solar PV generating capacity, with some new facilities being located at existing coal-fired power plants. Both will generate electricity that will be fed to the grid independently of the other. Although these two technologies will share a site and some assets such as grid connection, they will operate largely as independent units and not as integrated hybrids.

A limited number of coal-solar projects are true hybrids. These operate under an entirely cooperative arrangement where the two 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 form of hybrid technology integrates these two disparate forms of power so that they combine the individual benefits of each.

This approach can replace a portion of coal demand by substituting its energy contribution via input from a solar field. During daylight operation, solar energy can be used to reduce coal consumption (coal-reducing mode). As solar 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. When solar radiation increases again, the process is reversed, with solar input gradually reducing that of coal. Alternatively, input from the solar field can be used to produce additional steam that can be fed through the turbine, increasing electricity output (solar boost). 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.

Solar energy is usually harvested in one of two ways. The first is via conventional PV cells that convert solar radiation directly into electricity. The second is solar thermal, usually in the form of concentrated solar power (CSP), where radiation is used to produce heat (Fig. 1). These systems generally rely on a series of lenses or mirrors that automatically track the movement of the sun. They focus a large area of sunlight into a small concentrated beam that can be used as a heat source for a conventional thermal power plant. In all types of systems, a working fluid (such as high-temperature oil or, increasingly, molten salts) is
heated by the concentrated sunlight, then used to raise steam that is fed into a conventional steam turbine/generator. In addition to the solar collection system, a stand-alone CSP plant (not hybridized) will also require many of the systems and components, such as steam turbine/generator, found in a conventional power plant. For a coal-solar hybrid, most of these will already be in place and available as part of the coal-fired plant, greatly reducing the cost of each unit of electricity generated.

A number of solar collection systems are available commercially, some more effective than others. Systems that use two-axis tracking to concentrate sunlight onto a single point receiver (tower and dish systems) are usually more efficient than linear focus systems. Where they form part of a CSP plant, they can operate at higher temperatures and hence generate power more efficiently. However, they are also more complex to construct. The four main types of solar collection systems are as follows:

- Parabolic trough systems—solar energy is concentrated using sun-tracking parabolically curved, trough-shaped reflectors onto a receiver pipe that runs along the inside of the curved surface;
- Linear Fresnel systems—an alternative system that relies on the use of segmented mirrors instead of troughs;
- Power Tower systems (or central receiver systems)—these utilize sun-tracking mirrors (heliostats) to focus sunlight onto a receiver at the top of a tower (Fig. 2). A heat transfer fluid is heated in the receiver up to ~600°C and used to generate steam that is then fed to a conventional turbine-generator; and
- Parabolic dishes—these reflect solar radiation onto a receiver mounted at the focal point. They usually use two-axis tracking systems to follow the sun.

1.1 The first coal-solar hybrids

Coal-solar technology has been under consideration and development for some years. The world’s first true coal-solar hybrid power project was located at the Cameo Generating Station in Colorado, USA—the Colorado Integrated Solar Project (CISP). It was undertaken as part of the state’s Innovative Clean Technology Program, an initiative designed to test promising new technologies that had the potential to reduce greenhouse gas emissions and produce other environmental improvements. The system at the Cameo plant was put into operation in 2010.

Xcel Energy and Abengoa Solar partnered on this US$4.5 million demonstration that used sun-tracking parabolic trough technology to supplement the use of coal. The main aim was to demonstrate the potential for integrating solar power into large-scale coal-fired power plants to increase plant efficiency, reduce the amount of coal required and hence reduce conventional plant emissions and CO₂. It was also to test the commercial viability of combining the two technologies.

A 2.6-ha solar field housed eight rows of 150-m-long parabolic solar troughs (Figs. 3 and 4). In operation, this arrangement concentrated solar radiation onto a line of receiver heat-collecting elements filled with a mineral oil-based heat transfer fluid. This was heated to ~300°C before feeding to a heat exchanger where it preheated feedwater (to ~200°C) supplied to one of the Cameo plant’s two 49-MW coal-fired units.

The Cameo plant undertook a 7-month pilot/demonstration programme after which the station was retired and the CSP plant decommissioned. Overall, the results were considered positive. The addition of solar energy increased overall plant efficiency by >1%, and during the test period, coal demand and air emissions were reduced (~600 tCO₂, >900 kg NOₓ, and 2450 kg SO₂). The project...
confirmed that this type of supplemental application to an existing coal-fired boiler is feasible and would not interfere with normal generation operations. Integration and operation of the solar system with the existing coal-fired unit was deemed a success [5, 6].

For a time, several Australian utilities also showed interest in coal-solar hybrids and more than 20 coal-fired power plants were identified as having adequate solar resources. The potential capacity for incorporating solar energy with moderate-high prospects of proceeding were estimated at ~460 MWe, or ~1% of total Australian installed generating capacity. But not all power plant sites were considered suitable. Limiting factors included the lack of available land, low coal costs, and the remaining lifetime of some plants. Factors working in the technology’s favour included reduced coal consumption and plant emissions, and extended working life of power assets and coal resources. The concept of combining CSP with coal-fired plants was viewed fairly optimistically, although recently interest appears to have waned—in part because several major projects have failed to proceed, been abandoned or only operated in conjunction with coal for a limited period. For a variety of reasons, only one progressed to commercial operation.

In Queensland, CS Energy developed plans for a 44-MW solar thermal add-on to its 750-MW supercritical coal-fired Kogan Creek plant [7]. Heat from a Fresnel-based collection system was to be used to produce high-pressure steam and fed to the steam turbines, boosting electricity output. An estimated 35 600 t/yr of CO₂ (~0.8% of the plant’s total emission) could have been avoided. Construction began in 2011 (Fig. 5). However, unspecified technical difficulties and commercial issues eventually made the project economically unviable and led to its abandonment in 2016 [8].

In New South Wales, a solar collection system was also built at Macquarie Generation’s 2-GW coal-fired Liddell Power Station (Fig. 6). The project was put into operation in 2013 and incorporated a solar boiler used to provide saturated steam for preheating boiler feedwater [9]. Coal consumption was reduced and CO₂ emissions cut by ~5000 t/yr. However, in 2016 the solar project was closed down, the operator citing technical and contractual issues that had resulted in lengthy delays and commercial problems.

Coal-solar hybrid technology has also been investigated in a number of other countries that maintain major coal-fired power sectors, and significant work has been undertaken in, for example, South Africa, China and several European countries. Recent years have seen a number of feasibility studies and small-scale projects although none have yet led to large-scale, commercial deployment.

However, an interesting project is currently being developed in Chile. The country is experiencing rapid economic growth, and interest in the use of solar power has increased. As part of this, the potential of hybrid coal-solar plants has been assessed. Chile operates several electricity grids: the central grid has variable hourly demand, whereas the northern one experiences almost constant demand, mostly from the sizable mining industry located predominantly in the north.
Parts of Chile have significant potential for the application of solar power. Yearly total direct normal irradiation (DNI) levels are >3000 kWh/m² in most of the country, with >3500 kWh/m² to the north in the Atacama Desert, close to much of the mining sector. As part of increasing electricity supply in the region, a 5-MW coal-solar hybrid project is being developed by Engie and Solar Power at the existing 320-MW Mejillones coal-fired power plant. It is anticipated that the incorporation of solar power will boost plant output and reduce coal consumption (and hence plant emissions).

A second new coal-solar project is also underway in India. In a recent development, NTPC (formerly the National Thermal Power Corporation Limited) announced the start of a coal-solar hybrid project (the Integrated Solar Thermal Hybrid Plant – ISTHP) to be developed at its Dadri power plant. This will be the first Indian project to use solar energy to heat boiler feedwater with the aim of increasing plant efficiency and reducing coal demand. To save costs and manpower, the project will feature the robotic dry cleaning of the solar panels.

1.2 Challenges

Conventional thermal power plants and intermittent renewables such as solar power lie at different ends of the technological spectrum. Consequently, the combination of such disparate systems will inevitably throw up technical issues. Nevertheless, a number of system developers and power utilities believe that, with further development, coal-solar hybridization could hold considerable potential. Various challenges, however, remain for large-scale deployment—these may be political, technical or financial. Although the concept of hybridized power plants has existed for some time, its application, and hence bank of operational experience, remains somewhat limited.

From a purely practical point of view, any solar-based system needs a consistent source of sunlight of adequate intensity, which clearly limits possible locations. Although arguably less important for PV systems, it is crucial for those based on solar thermal technology. A solar collection system will require land close to the existing power plant, possibly up to several thousand hectares. Furthermore, coal-fired plants are usually located near a source of cooling water, meaning that they are rarely located in the arid high desert locations well suited to solar thermal applications.

A major challenge is to increase the solar share of coal-solar hybrids. To date, input from the solar component has tended to be limited, often as a consequence of their application to retrofit applications on ageing plants as opposed to new build. There is some consensus that the sector needs bigger hybrid projects based on highly efficient, newly built coal-fired plants; this would provide more scope for improved efficiency and better economics. Furthermore, the addition of thermal storage could improve dispatchability and help minimize the cost of electricity. Alongside economic issues, as every project is essentially unique, each will bring its own combination of technological issues that have to be resolved. However, it is anticipated that the ‘live’ projects being developed in countries such as Chile and India will provide useful data and operational experience, hopefully encouraging further uptake of the technology.

1.3 Future developments

As with any generating technology, a system based on solar energy must make economic sense. Thus, it is important to keep capital and operating costs at acceptable levels. In some locations, recent development has focused on stand-alone CSP systems (i.e. not hybrids). However, the cost reductions these are achieving will also have a positive impact where they form part of a coal-solar hybrid. The opportunities for reducing the cost of CSP plant are encouraging. The commercial deployment of the technology is still at a relatively early stage, but as development proceeds and plants increase in size, costs are likely to fall as components benefit from mass production and increased competition between vendors.

Technology development continues, aimed at reducing system costs, increasing the efficiency of solar-electricity conversion and minimizing the environmental footprint. Further refinement and research is gradually improving plant components and systems. Several key areas have been identified where cost savings would be particularly beneficial. These include reducing the cost of the solar field through improved designs, mass production, cheaper components and the introduction of new heat transfer fluids capable of operating at higher temperatures. Improved thermal storage systems also have an important role to play.

A number of major technology developers are continuing to pursue these goals. Some suggest that if a new power plant was designed and built based on the hybrid concept from the outset, a much greater solar share (possibly up to 30–40%) could be realistic. So far, input from the solar system has tended to be somewhat on the low side. This has largely resulted because projects have been based on the retrofitting of, sometimes outdated, coal-fired plants. As a result, practical issues have tended to limit the solar contribution to perhaps around 5% or less.

2 Coal-natural gas cofiring

Another option attracting the interest of some power utilities is that of cofiring natural gas in coal-fired boilers. This technique can be instrumental in improving operational flexibility and reducing emissions. It avoids the intermittency issues of renewables such as solar power, but clearly retains some of the disadvantages associated with fossil fuels in general.
Both coal- and gas-based generation are vital in powering many of the world's developed and emerging economies. Both are used to provide a secure and uninterrupted supply of electricity, needed to ensure that economies and societies can develop and prosper. In some countries, coal provides much of the power, whereas in others gas dominates. However, there are many instances where the national energy mix includes combinations of the two. Each brings its own well-documented advantages and disadvantages, but recent years have seen a growing interest in means by which these two fuels might be combined in an environmentally-friendly and cost-effective way.

Although coal-fired power plants in many countries already use natural gas for start-up and warming operations, the amounts used are often quite limited. But why would a plant operator want to cofire gas in larger amounts? What sort of benefits might it provide? As noted earlier, changing market conditions are increasingly forcing many plants to find new means of operating so as to keep them clean, efficient and economically viable. Replacing part of the coal feed with gas and burning the two together in the plant's steam generator can help enhance both fuel and operational flexibility, vital in today's often challenging electricity markets.

In many countries, environmental legislation continues to be introduced to reduce levels of \( \text{SO}_2 \), \( \text{NO}_x \), particulates, mercury and, more recently, \( \text{CO}_2 \), and increasingly operators face the dilemma of what to do with their plants. To avoid investing in upgraded emissions control equipment, they may decide to simply close the plant on economic grounds. Many plants in the USA, for example, are currently in this situation. If finances allow, the operator could possibly opt for complete conversion to 100% natural gas firing, but this may be too expensive or impractical. Alternatively, it may be possible to modify the plant so that natural gas can be added, helping to keep it in service. Cofiring with gas seems a promising option for at least some existing coal-fired plants, and a number of utilities are considering (or are even in the process of) converting their coal plants for cofiring, enabling them to continue operating using a mix of coal and natural gas (Fig. 7). Importantly, some conversions allow the ratio of coal-to-gas to be varied, providing a useful degree of flexibility in terms of fuel supply and plant operation.

Potentially, gas can be added to an existing system in a number of ways. Some replace a portion of the main coal feed, whereas others use gas as a means for minimizing emissions of species such as \( \text{NO}_x \). The amount of gas used for some types of application will normally be less than if the plant is converted to actually cofire gas in the true sense. This allows much greater volumes to be fed directly into a boiler and burned simultaneously with the coal feed. Depending on the individual plant and operational requirements, the existing unit can be configured in a number of ways so that cofiring becomes a practical proposition. It may be a case of replacing oil-fired igniters or warm-up guns with gas-fired equivalents, one of the simplest options. But should a plant operator wish to consistently put even more gas through his plant, it is likely that gas firing will need to be incorporated into the main burner system; there are dual or multi-fuel burners suitable for this, available commercially from a number of suppliers [10].

As with solar addition, there can be various pluses and minuses involved. Some of the main attractions of cofiring include:

- possible adaptation/reuse of existing infrastructure and control systems. Many coal-fired power plants already use natural gas as a start-up or back-up fuel, so the necessary infrastructure and control systems for feeding gas to the boiler may already be in place;
- enhanced fuel flexibility. Cofiring removes total reliance on a single source of fuel, creating fuel flexibility. If a problem arises with availability of one fuel, the plant has the ability to maintain operations by switching to the other. Similarly, increases in the price of either fuel can be countered by changing the cofiring ratio such that the cheaper fuel predominates;
- cost savings can be achieved by switching to the cheapest fuel at the time. It may also be possible to switch to lower-cost coals without the risk of lost capacity;
- some emission control upgrades may be reduced in scope, delayed, or avoided, depending on the coal quality, level of gas cofiring intended, and the regulatory environment;
- improved operational flexibility. Cofiring can reduce warm-up times, allowing the unit to be brought on line faster than an unmodified equivalent, as well as enabling faster ramp-up. A faster start-up can help minimize higher emissions sometimes experienced during this phase. This technique allows some US power plants to comply with the federal Mercury and Air Toxins Standards;

![Fig. 7 Alabama Power's Gaston power plant in the USA. One unit now starts up on gas and regularly cofires gas up to two-thirds of its rated capacity (photograph courtesy Alabama Power)](image-url)
cofiring can provide a significant reduction in the minimum unit load achievable, an important factor for many coal-fired power plants. Also, by cofiring a significant amount of gas when in low-load conditions, the minimum operating temperature of a plant’s selective catalytic reduction (SCR) unit (where fitted) can be maintained;

- less coal throughput will reduce wear and tear on pulverizers and coal handling systems, as well as reduce associated operation and maintenance (O&M) costs;
- reduced coal throughput generates fewer solid and liquid plant wastes. Bottom ash, fly ash, FGD scrubber sludge or gypsum, mill rejects, and various other waste products will be reduced as well as handling and disposal costs; and
- emissions to air will be proportionately lower. O&M costs of environmental control systems such as FGD, SCR units, and ESP or bag filters are likely to be lower. In the case of SCR systems, ammonia use will be less and extended catalyst life is likely. Where mercury control systems are in place, less activated carbon will be required.

As with any technology, there will be drawbacks. An obvious 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 in some way, existing infrastructure may be adequate. If not, additional supply and control equipment may be required. Depending on the overall length and any local constraints, costs for a new gas pipeline can be considerable. 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 much more expensive and less readily available in some other economies. Even in the USA, there are concerns that prices could increase significantly in the future as political and environmental pressures on hydraulic fracturing and investments in gas export facilities could drive up the price of gas, closer to those seen in Europe. Higher gas prices could cancel out any advantages and cost savings provided by cofiring.

In the USA, the Environmental Protection Agency (EPA) has suggested that, under some circumstances, cofiring could be an alternative to applying partial carbon capture and storage (CCS) to coal-fired power plants. The EPA has advised that new emissions standards could be met by cofiring 40% natural gas in highly efficient supercritical pulverized coal power plants. However, some industry observers think that more than this level would be needed and that, for this to be achievable, the boiler would need to be specifically designed to operate in this manner.

Various technical issues will need to be considered when a switch to cofiring is contemplated. For example, there can be significant impacts on heat transfer within the boiler. The heat transfer characteristics of natural gas and coal flames are markedly different and, in some cases, original heat transfer surfaces may be inadequate for increased natural gas firing. If appropriate measures are not taken, problems with metallurgy can arise and major plant components run the risk of becoming unreliable. Gas supply may also be an issue. In some locations, supply restrictions may limit the maximum amount available. Furthermore, seasonal restrictions may apply, giving priority to other applications such as home heating.

2.1 Future prospects

The cost of generating electricity from coal or gas can be similar. Even slight changes in fuel price can result in significant swings in production costs, and this can create market opportunities for utilities that have both gas- and coal-fired assets. Cofiring can be a possible option, allowing pricing and market conditions to drive the fuel choice and mix. Substituting some coal input with gas is considered to be a low-risk option, allowing utilities to better meet changing market requirements.

In the coming years, natural gas is forecast to continue partially replacing coal for power generation in some major economies. The operating advantage is expected to go to utilities with diversified fleets capable of switching between the two as the market price of each fluctuates. This will be of particular advantage during periods of flat electricity growth, such as that experienced in the USA in recent years.

A number of utilities have already adopted gas cofiring and others are considering converting some of their coal plants such that they can operate on a mix of the two. In the USA, a number of plant operators are currently investigating the test firing of natural gas to determine the long-term feasibility of either full conversion or dual-fuel firing. Some are engaged in feasibility studies to evaluate the possible ramifications of cofiring. Others have already switched.

Adding gas to coal-fired plants offers utilities the possibility of rapid response to changes in load demand and deep cycling capability, but retains the ability to fire low-cost coal. In economies where electricity demand fluctuates, a power plant that can cycle quickly to meet peaks and troughs, and also ramp down during periods of low demand, is more likely to be profitable. However, most coal-fired units can only operate as low as 30–35% load and still sustain good combustion, restricting the plant’s ability to cycle. Furthermore, coal plants can be slow to cycle up to full load: it can take 12 hours or more to ramp up to load from a cold start. A plant capable of switching to gas at low loads and taking load down even farther, then switch back to coal at higher loads, could have a significant advantage over the competition.

Cofiring can offer increased fuel flexibility and potentially this can provide significant fuel and operational savings. Many coal-fired plants were built in an era when coal was cheap, environmental pressures were low and competition from other generating sources was limited. Increasingly, many of these plants are now expected to operate in non-baseload modes, for which they were not
designed. They need to adapt and evolve to survive in the longer term, and the ability to operate on fuels that they were not originally designed for will be an important factor. Hence, increased fuel flexibility is growing in importance.

The biggest near-term potential market for cofiring appears to be the USA, where a number of utilities are looking to extend the working lives of their plants whilst simultaneously reducing their environmental footprint. Cofiring can help reduce emissions, improve operational flexibility and allow faster start-ups, bringing plants on line more quickly and cleanly. Elsewhere, the overriding factor is likely to be the price and availability of gas. Although this is currently inexpensive in the USA, it is much more costly or unavailable in many other locations. Furthermore, in some countries, exporting natural gas is a more lucrative option than using it in domestic power plants—exports may take priority. Thus, the viability of an individual project will depend on the particular set of circumstances prevailing.

Apart from the USA, there are a limited number of plants in countries such as Indonesia and Malaysia that cofire coal and gas (Fig. 8) and also new projects in development. However, a major factor is the availability of a reliable supply of gas at a suitable price. In some locations, although affordable for limited application, gas is too expensive for bulk use. Coal is often cheaper and more easily available. For any new potential project, as with coal-solar hybrids, various economic, operational and environmental factors need to be considered on a case-by-case basis. But, compared to solar, opportunities for cofiring are less restricted as there are many more locations where both coal and natural gas are readily available.

### 3 Closing thoughts

Nearly all major economies rely on coal to some extent and many emerging ones do likewise. Despite competition from natural gas, nuclear power and renewable forms of energy, coal will continue to be used widely for many years and in considerable quantities. However, coal use in general is coming under increasing scrutiny, with power generation often singled out as a major source of pollution. In many countries, policies and legislation have been introduced to encourage the greater uptake of alternative systems that include gas-fired generation and renewables such as wind and solar power. Renewables are often promoted strongly via emission reduction targets, obligatory renewables mandates, air quality directives and emissions trading schemes. Financial incentives or various forms of subsidy are usually involved.

The biggest drawback with wind and solar power is their inherent intermittency and the relatively high cost per unit of electricity generated. This variability impacts negatively on the operation of coal-fired power plants feeding into the same grid. Many of these were designed to work on steady-state baseload, but to accommodate input from renewables, are now forced to operate on a much more flexible or cyclical basis. Repeated start-stops, cycling or load-following inevitably increases wear and tear on major plant components and decreases overall efficiency. However, this mode of operation has increasingly become the norm, and cost-effective ways to enhance their performance in terms of operating flexibility, environmental impact and economics are being sought.

These goals could be achieved in a number of ways. In the case of improving plant flexibility, these include combining coal with solar energy or natural gas. Although both techniques are already (or have been) used on a commercial basis, neither is currently used widely. Under the appropriate conditions, incorporation of either form of technology offers a number of advantages to coal-fired power plants. But, clearly, both have their limitations. Solar-based projects will only make sense in locations that receive consistently high solar radiation. Similarly, cofiring with natural gas will only be possible where there is a reliable, affordable supply of gas.

Both systems have the potential to improve operational flexibility, moderate plant costs and reduce emissions. Each can provide benefits when retrofitted to existing coal-fired power plants, although their greatest potential appears to lie in new-build units, where each can be integrated fully at the design stage. Enhancing flexibility and efficiency, and reducing the associated environmental footprint, will become increasingly important in maintaining an affordable and effective coal-fired power sector.

How are these two technologies likely to influence the amount of coal consumed around the world? On a global basis, coal-solar combinations are unlikely to have a major impact, although they could be of much greater significance in some niche markets. If solar power was used to replace a significant amount of coal fed to a power plant

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**Fig. 8** The 4-GW Suralaya plant, Indonesia’s largest coal-fired station. The newest unit is capable of cofiring differing amounts of pipeline natural gas or LNG, as well as fuel oil or biomass (photograph courtesy of Indonesia Power)
(operating in ‘coal saver’ mode), the overall amount could actually decrease, although this would not be the case with plants operating in ‘solar boost’ configuration. However, hybridization can offer other benefits such as lower coal costs, reduced plant O&M requirements and a lower environmental impact. These may be enough to keep certain plants in service.

The second technique considered is the cofiring of natural gas in power plants that currently rely on coal as their main fuel. Many such plants already use relatively small amounts of gas alongside their coal feed, although only a limited number can be considered as true cofiring. The addition of greater volumes of gas can offer significant benefits in terms of operational flexibility, economics and environmental impact and could offer a possible lifeline to some plants struggling to meet increasingly stringent environmental limits. Compared to solar hybridization, opportunities for cofiring are much less restricted as there are many locations where both coal and natural gas are available. However, as with coal-solar hybrids, cofiring projects need to be evaluated on a case-by-case basis to ensure that the relevant factors are addressed.

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