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Foreword

The member States of the United Nations Economic Commission for Europe (ECE) rely heavily on fossil fuels – their share in total primary energy supply in the ECE region is around 80 per cent. Despite impressive progress in the deployment of renewable energy sources, the stark reality is that under any plausible long-term scenario fossil fuels will remain a critical part of the energy mix in the coming decades. Sustainable management of fossil fuels -- and their interplay with renewable energy sources -- is therefore one of the keys to achieving the developmental, societal and environmental objectives of the 2030 Agenda for Sustainable Development.

Given the inherent variability of renewable energy, increasing the flexibility of coal power plants' operations could allow for a faster deployment of renewable energy sources, thereby reducing the carbon intensity of electricity generation. With proper design and operating procedures, it seems possible to support broader renewable energy integration using coal as a flexible balancing resource.

This report is the product of a collaborative effort between a group of researchers from Duke University and ECE's Sustainable Energy Division. The researchers examined current technological, social and economic developments and focused on costs and case studies of coordinated operations of fossil fuel-fired power plants and renewable energy. This report provides ECE member States with options for consideration as they strive to transform their electricity systems and prepare for a low carbon future.

Olga Algayerova
Executive Secretary
United Nations Economic Commission for Europe

EXECUTIVE SUMMARY

In recent years there has been rapid change in the electricity sector. Faced with the challenge of climate change, the coal industry is under pressure: consumption in some countries declined and energy policy design has focused on accelerated deployment of renewable energy. However, there are drawbacks that prevent broader penetration of renewable energy. It is therefore important for policymakers to identify ways to leverage the benefits of renewable energy while preserving the availability, affordability and reliability of electricity.

Several studies have explored the possibility of coordinating fossil fuel-fired power plants with renewable energy. This report presents four options: using solar thermal energy to help power generation in pulverized coal power plants; using solar thermal energy to compensate for the energy penalty of Carbon Capture and Storage (CCS); using wind power and water electrolytic hydrogenation technology to help Integrated Gasification Combined Cycle (IGCC) power plants; and using wind power directly to offset the energy penalty of CCS.

Solar-aided power generation is a hybrid system in which solar thermal and fossil energy technologies are used in combination. The introduction of solar thermal technology can help raise the overall efficiency of a power plant. Research shows that hybridization reduce the costs of electricity compared to a pure renewable energy power plant; it also helps eliminate a large part of variability in power output in stand-alone solar power systems. The electricity output is reliable and fully dispatchable. There are several pilot projects around the world, and abundant research is available.

It is also viable to use solar thermal energy to deal with energy penalty brought by CCS. Studies show that the energy penalty incurred during solar hours will be approximately zero if the solar plant has enough capacity. This technology will add to capital costs, land occupation, and complexity of operations.

IGCC plants produce synthetic gas (syngas) to turn turbines and generate electricity so the emissions of particulate matter and other harmful species can be reduced. These plants are good candidates for CCS. It has been proven as viable to use wind energy to compensate for energy penalty due to CCS. By not integrating the wind farm directly into the grid, and instead combining it with a coal-fired power plant, the integration costs can be avoided as the power plant uses the wind energy directly instead of trying to dispatch it out to the grid.

Wind power and water electrolytic hydrogenation technology can be used to help IGCC power plants. A fraction of the coal requirements for producing hydrogen could be reduced economically by using wind power for electrolytic hydrogen production, thereby lowering total CO_2 emissions from the IGCC plant. Several pilot projects around the world demonstrated viability of the idea.

Certain sub-regions within the ECE region are particularly promising in terms of solar thermal energy development, while others have abundant wind resource. In terms of policy support, the majority of countries have adopted energy and carbon reduction strategies. These joint technologies can accelerate attainment of objectives.

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Introduction

Business case for synergies between flexible coal and renewable energy

The fuel mix and operation of the electricity sector worldwide is undergoing rapid changes. Although current reserves of fossil fuels could likely satisfy energy demand for the foreseeable future [1] [2], climate concerns, market developments and public policy goals are increasing the penetration of renewable energy technology at a fast pace. The reference case presented in the International Energy Outlook report published by the United States Energy Information Agency (EIA) [3] identifies renewable sources of electricity as the fastest growing source of electricity generation, projected to supply 29 per cent of global electricity demand by 2040. The International Energy Agency (IEA) also refers to renewable energy as one of the winners in the race to meet energy demand growth by 2040 [4].The primary drivers of increased shares of renewable energy in the electricity sector are:

1. **Growing concerns over negative impacts of emissions from fossil fuel-fired electric power plants:** A broad range of studies have demonstrated the widespread environmental impacts of emissions from fossil fuel-fired electric power plants. These emissions can negatively affect climate and health. Renewable power sources are low-carbon technologies that can be used to limit emissions from the electricity sector.
2. **Volatility of fuel prices:** Fossil fuels often form the bulk of exported and imported goods for a nation. As a result, the price of fuels is often subject to fluctuations given uncertainties in trade agreements, depletion of supply from a given source, geopolitics of the energy system etc.
3. **Quest for energy independence and resilient power grids:** Developing a diverse portfolio of energy resources would allow reducing the dependence of the power grid on a single resource and improving its resilience to disruptions in supply.
4. **Shifts in consumer behaviour:** Recent surveys demonstrate a growing trend in energy consumers transitioning from passive buyers to active users. These consumers are interested in installing solar panels and other sources of residential and community scale renewable power generating units to actively manage their energy consumption [4].

While renewable power has established itself as a crucial component of an environmentally sustainable and resilient power grid, there are significant drawbacks to the design of power grids solely dependent upon these sources. Some key consequences of the variability, uncertainty and low marginal costs of intermittent renewable power sources such as wind and solar include [4]:

1. **Driving out 'firm capacity' from the fuel-generation mix:** Once a renewable power-generating unit is installed, the operating costs are very low compared to those of conventional fossil fuel-fired units. Without the proper market adjustments, large-scale deployment of renewable energy in power systems may result in fossil fuel-fired plants not being able to recover their fixed costs, and being forced to retire. However, because some renewable energy can be variable/intermittent, power systems may have insufficient 'firm capacity' to reliably meet demand if conventional sources of generation retire.
2. **Volatile electricity prices:** Extremely high electricity prices may occur in markets that have insufficient and/or inflexible fossil fuel-fired capacity to compensate for variable or insufficient power output from renewable sources.

In addition, despite rapid technological advancements, large-scale energy storage infrastructure is still costly and hence unlikely to provide in the short/mid-term a pathway for exclusive reliance on renewable power in the transition to a sustainable, low carbon electricity sector. Fossil fuel-fired electricity (especially coal and natural gas) is often cheaper than most combinations of storage with industry scale renewable power generation, and hence is likely to continue to be needed as a source of reliable, affordable electricity [4], despite reduction in coal consumption in recent years [2]. In the absence of strategic planning and operation, it may well be possible that emissions from fossil fuel-fired electricity production will continue to grow in spite of higher deployment of renewable power in the system. [5]

Under such circumstances, it is important for governing bodies, planning authorities and policy organizations to identify alternatives to leverage the benefits of renewable power in a way that is both economically viable and preserves the reliability and quality of electricity supplied to consumers. Flexible operation of fossil fuel-fired plants provides a way to incorporate intermittent renewable power into the grid [4] [6].

Although historically most of large-scale coal-fired power plants have operated to cover base-load by producing power at a fairly constant level, both new and existing coal plants have flexibility of operation [7] (even though there maybe economic fallouts from increased wear and tear) and therefore are able to operate as peaking plants.

Although uncontrolled coal-fired power plants are an important source of CO_2 emissions, the lower volatility of coal prices relative to oil and natural gas, together with the possibility of using Carbon Capture and Storage (CCS) technologies increase their chances of being an important part of the generation mix. However, the operation of CCS technologies in power plants is associated with a reduction in net power output, and hence reduces the firm-energy that it can provide to the system where it operates. A number of studies [5] [8] [9] conclude that under certain technical and economic conditions it may be economically advantageous to use renewable power to compensate for this reduction in electric power output due to CCS operation in fossil fuel-fired plants.

The economic and environmental benefits of coordinated operation of coal-fired power plants with solar, wind, and biomass have been explored in a number of studies. This report presents an overview of the potential of joint operations of CCS with renewables by looking at four case studies within ECE member countries:

(a) Solar aided power generation in pulverized coal plants through the use of solar thermal technology;
(b) Solar aided CCS in pulverized coal power plants;
(c) Integrated Gasification Combined Cycle (IGCC) plants that co-ordinate operation with wind power through a technology called water electrolytic hydrogenation;
(d) Co-located wind power to offset energy penalties due to CCS operation in IGCC plants.

The case for replacing the lost power generation capacity of a coal-fired power plant due to CCS by co-locating a wind plant is harder to make than the case for colocation of a thermal solar plant. This is because while a thermal solar plant produces steam that can be integrated directly into the power plant; a wind farm generates electricity that could not be generated in situ. Installing wind power plants in the regions with the best wind resources and ensuring the proper power transmission capacity is in place would be a sensible way to make up for the CCS energy penalties of any plant.

However, because of the lack of power transmission capacity, and the high costs and difficulties of making it available, the potential of co-locating fossil fuel-fired power plants with CCS with wind power could be explored.

The purpose of this report is not to provide an exhaustive list of renewable power and coal power plant combinations that could be implemented in the ECE region. Instead, through case study analyses of practical instances of coordinated operation of coal and renewable electric power, the aim is to provide readers a clearer understanding of the advantages and challenges of the implementation of such technologies, especially within ECE member countries.

The remainder of this report is organized as follows:

Part 1 describes the cases studies coordinating solar thermal technology with pulverized coal units.
Part 2 describes the cases coordinating the use of wind power with IGCC plants.
Part 3 summarizes the findings of the case studies.

Part 1: Coupling Solar Thermal Energy with Pulverized Coal Power Plants in the ECE Region

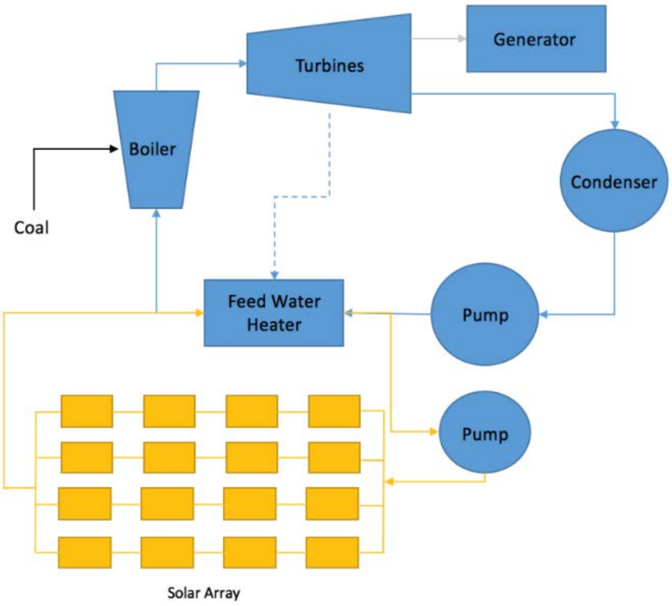
1.1 Pure solar aided power generation

Solar aided power generation (SAPG) is a hybrid system in which thermal solar and fossil energy technologies are used in combination to generate electricity. For coal plants, there are four approaches to realize the hybridization: redundant system hybridization; parallel fossil heater hybridization; solar augmented hybridization and solar preheat hybridization. [10]

The preheat hybridization (see Figure *1.*) has been discussed in the current literature, from both technological and economic perspectives [10] [11] [12] [13] [14] . The basis of the SAPG concept is to use solar thermal energy to replace the bled-off steam in the regenerative Rankine power cycle. Extracted bled-off steam is used to preheat feed water and it has the effect of increasing the thermal efficiency of the cycle [15]. This improvement in efficiency sacrifices partial work output of the turbine due to the reduced steam mass flow. A typical solar aided coal power plant with preheat hybridization uses solar steam to replace these extractions [16]. Studies have proven that this kind of power generation system is more efficient [17, 18].

A preheat-hybrid power plant can operate in two modes. If the solar thermal energy collected by the array is used to reduce demand of energy from coal combustion, then it is said to operate in coal-saving mode. If the solar thermal energy collected is used to increase the plant’s generation capacity, then it is said to be operating in power-boosting mode [19]. A thermodynamics study showed that SAPG is capable of raising the capacity of a coal plant by 5 per cent if operated under low pressure feed water preheating option; and 10 per cent if operated under high pressure feed water preheating option [20].

Figure 1
Model of SAPG preheat hybridization in a Rankine Cycle



Water/steam flow through the blue lines. Solar energy flows through the yellow lines. The feed water heater takes solar energy to preheat water before it enters the boiler. The dashed blue line from turbines to feed water heater implies that steam can be withdraw from turbine at different stage when they have different pressure and temperature; a power plant can have single or multiple withdraws of steam from turbine to feed water heater as well.

1.1.1. Criteria for applying SAPG

The United States National Renewable Energy Laboratory (NREL) defined in 2011 criteria for identifying U.S. fossil fuel-fired power plants suitable for solar aided power generation [21]. These criteria cover six aspects of a plant: age, capacity factor, annual average direct normal irradiance (DNI) at its location, amount of available land, topography of the available land, and solar use efficiency (see Table 1.)

Table 1
Criteria for applying SAPG in the United States

Plant Characteristics	Should be	Threshold	Unit
Age	<	30	Years
Capacity Factor	>	15	per cent
Average DNI	>	4	kWh/m^2 per day

Available Land	>	0.05	Acres/Fossil Fuel Capacity MW
Topography of Available Land	<	5	per cent of Slope
Solar Use Efficiency	>	30	per cent

For plants that meet the prerequisites mentioned above, there are still a number of factors that must be consider to assess the viability and efficiency of a SAPG retrofit. First, the solar field requires water of high quality. However, once water goes through the boilers, its quality degrades and hence directly circulating water/steam that comes out of the boiler, through the solar field is problematic. Second, the current design of the boilers, their pressure and temperature, and the number of existing bleeds in the turbine etc., influence the efficiency of the hybrid system. [22]

1.1.2. Benefits and drawbacks

From a technology standpoint, SAPG is advantageous, especially compared to a pure solar power plant. A solar-aided system can eliminate a large part of variability in power output in solo solar power systems. The electricity output is reliable and fully dispatchable. Solar-aided systems help reduce carbon emissions while maintaining the same level of electricity output. In addition, if used exclusively in a fuel-saving mode integrating the solar energy does not require increased power transmission capacity.

However, there are also disadvantages when it comes to real system management. This type of hybridization requires a power plant to satisfy both the criteria of infrastructures listed in section 1.1.1, and the criteria for adding a solar preheating system nearby. Operating the system might not be easy as well. Solar preheating can lead to an airflow of 2600 m^3/s, which might cause safety concerns [20]. In addition, the variability and uncertainty of solar radiation require of the fossil fuel plant enough ramping capability if a stable power output is desired.

1.1.3. Pilot projects around the world

There are three major pilot projects in the world using SAPG technology with coal as listed below.

Table 2

Pilot Projects of SAPG technology around the world

Project Name	Country	Organization	Status
Colorado Integrated Solar Project	US	Xcel Energy	Currently Non-
Kogan Creek Solar Boost	Australia	CS Energy	Currently Non-
Liddell Power Station	Australia	Macquarie	Operational

The Cameo project [30] located in Palisade, Colorado, United States, is a parabolic trough solar field constructed to provide supplemental heat for the power generation for unit 2 at the Cameo Station. The capital cost of building up this concentrated solar, which covered an area of 6,540 m^2 was US$ 4.5 million (in 2010).

The Kogan Creek Solar Boost project [31] located in Chinchilla, Queensland, has a solar collector field with a length of 500 m and a width of 36 m, which gives an area of 180,000 m^2. The costs of this 44 MW project were approximately $A 105 million in year 2012 (US$ 79.72 million equivalent, under the exchange rate of $A 1 equals to US$ 0.76).

The Liddell Power Station [32] also located in Liddell, New South Wales has an area of 18,490 sm^2. The 9 MW solar boiler feeds steam into the existing 2,000 MW coal-fired power station. This project received $A 9.25 million in 2012 from the New South Wales Government Climate Change Fund Renewable Energy Development Program.

1.1.4. A case study in Greece

A study from Democritus University of Thrace in Greece assessed a solar-aided 300 MW lignite fired power plant in Greece [33]. This plant is the most recently built power plant in the region of Western Macedonia in Greece. The normal insolation in that area is on average 800 W/m^2 (daily insolation 4.2 KWh/ m^2 equivalent [34]).

The University modeled solar and power cycle performances under both power-boosting mode and coal-saving mode. Their results show that under power-boosting mode the maximum capacity of the proposed 120,000 m^2 solar field can reach 27 MW. Since the plant’s internal energy requirements amount to 25 MW, solar aided generation technology enables it to provide 302 MW to the grid, and hence results in an increase of 9.8 per cent of net power capacity, from its normal value of 275 MW.

An economic analysis of this 120,000m^2 solar field showed that the cost of electricity would be 75.25 €/MWh under the power-boosting mode, assuming a coal price of € 18/tonne yielding a 4.5-year payback period; 76.01 €/MWh under the coal-saving mode yielding a 5.5-year payback period.

1.1.5. General cost and benefit estimation

The Levelized Cost of Electricity (LCOE) of an SAPG power plant depends on the attributes of both the coal plant and the accompanying solar preheating system. A simple LCOE analysis using the calculation recommended by the U.S. National Renewable Energy Laboratory [23] (see Equation 1.) has been conducted based on assumptions listed in Table 3.

Equation 1. Calculation of Simple LCOE (units of each term are presented inside parenthesis)

$$Simple\ LCOE\ (\frac{US\$}{MWh}) = \frac{Overnight\ Capital\ Cost(US\$) * Annualizing\ Capital\ Recovery\ Factor(year^{-1}) + Annual\ Fixed\ O\ \&M\ Cost(US\$)}{365 * 24 * Capacity\ Factor} + Fuel\ Cost(\frac{US\$}{MBtu}) * Heat\ Rate(\frac{MWh}{MBtu}) + Variable\ O\&M\ Cost(\frac{US\$}{MWh})$$

$$Capital\ Recovery\ Factor = \frac{i * (1+i)^n}{(1+i)^n - 1}$$

where *i* stands for the interest rate and n stands for the number of annuities received

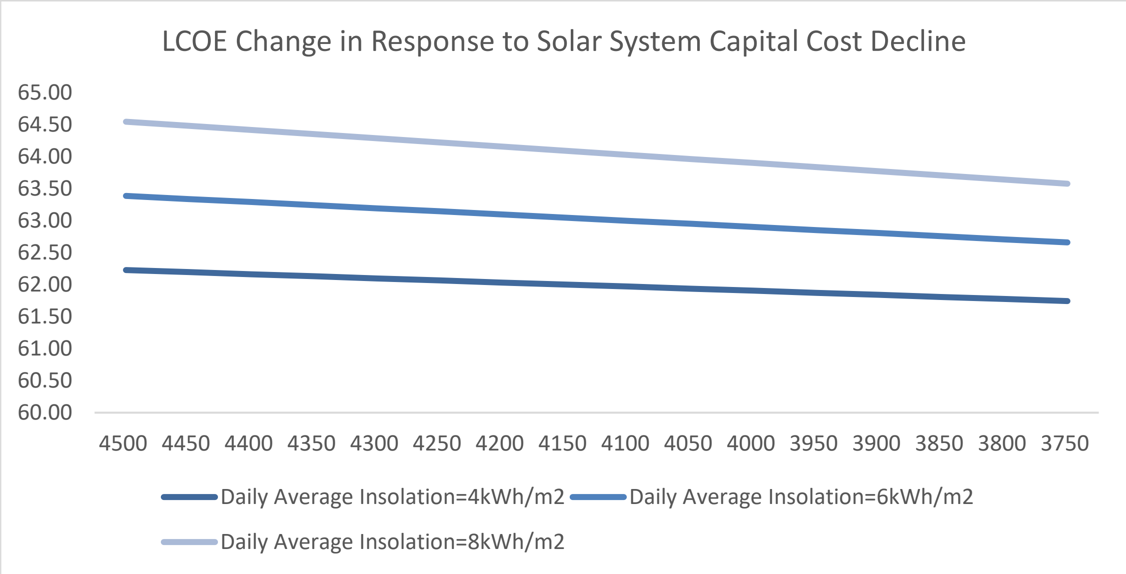
Table 3
Identified assumptions of an SAPG coal power plant

System		Attribute	Unit	Value Assumed
dSolar System	Production	Daily Average Insolation	kWh/m^2	8
		Solar to Electricity Efficiency	per cent	10.00
		Capacity factor	per cent	40.00
		Area of Solar array	m^2	120,000
	Financing	Capital Cost	US$/kW	3,750
		Cost of Solar Field	US$/m^2	700
		Annual O & M of Solar	US$/kW	50
Coal System	Production	Coal Plant Capacity Factor	per cent	75.00
		Coal Plant Capacity	MW	1082
		Coal Plant Heat Rate	Btu/kW	10,692
		Coal Heating Value	Btu/lb	13,000
		Coal to electricity Efficiency	kWh/to	2,430.13
	Financing	Capital Cost	M$/MW	3
		Annual O & M of Coal Plant	M$/MW	0.025
		Cost of Coal	US$/ton	50
Plant as a Whole		Plant lifespan	years	25
		Discount Rate	per cent	3

Given a fixed amount of available land, the capacity of the system increases as the daily average insolation grows stronger. For example, when daily insolation is 4 kWh/m^2 day solar collectors covering an area of 12,000 m^2 will result in the capacity of this system being 80 MW; when the daily insolation increases to 6 kWh/m^2, the capacity will grow to 120 MW; for a plant which has an insolation of 8 kWh/m^2-day n, the same 12,000 m^2 will allow a 160 MW of capacity.

The graph in Figure 2. presents how the LCOE of the hybrid plant decreases in response to a decline in capital costs. A study by Black and Veatch [24] indicates that the average capital cost (US$/kW) is expected to drop from 4,500 in 2020 to 3,450 in 2050. The model reports that the LCOE of plants with different insolation level decline to different extents. For a plant owning an 80 MW solar augmentation, LCOE drops by US$ 0.48/kWh; for a plant owning a 120 MW solar augmentation, LCOE drops by US$ 0.72/kWh; for a plant owning a 160 MW solar augmentation, LCOE drops by US$ 0.97/kWh.

Figure 2
LCOE drop in response to solar system capital cost decline



The most obvious benefit of adopting SAPG is saving coal while maintaining the same electricity output level. To study this benefit quantitatively, a simple model has been set up using a series of assumptions (listed in Table 4.) The model calculates annual electricity output supported by solar energy and therefore estimates the coal saved and CO_2 emissions reductions from using the SAPG system.

Table 4.
Assumptions in the Model

Attributes	Unit	Value Assumed
Area of Solar Array	m^2	120,000
Capacity factor of the Array	per cent	40
Coal Plant Nominal Heat Rate*	Btu/kWh	10,692
Coal Heating Value	Btu/lb	13,000
CO_2 Emission Rate*	lb/MWh	2,241.5
CO_2 Equivalent Emission Rate*	lb/MWh	2,258.2

* the assumed coal plant nominal heat rate and emissions rates are equal to the average value of coal plants whose nameplate capacity is greater than 100 MW and capacity factor is greater than 10 per cent in the US reported in the egrid database of 2014 [25]

According to a report by the International Renewable Energy Agency different types of concentrated solar power (CSP) technologies have annual solar-to-electricity efficiency ranging across 11 per cent to 25 [26]. Three scenarios of average daily solar insolation (equal to 4, 6 and 8 kWh/m^2 per day, typical of places such as Dublin in Ireland, Odessa in Ukraine, Limassol in Cyprus in June according to the 10 year-average data provided by National Aeronautics and Space Administration (NASA) [27]) have been considered in this model. The annual amount of coal and CO_2 emission saved from solar augmentation under coal-saving mode at different insolation level using equipment of different efficiency is presented in Figure 3 and Figure 4.

Figure 3
Annual coal saved by adopting solar augmentation (tonne)

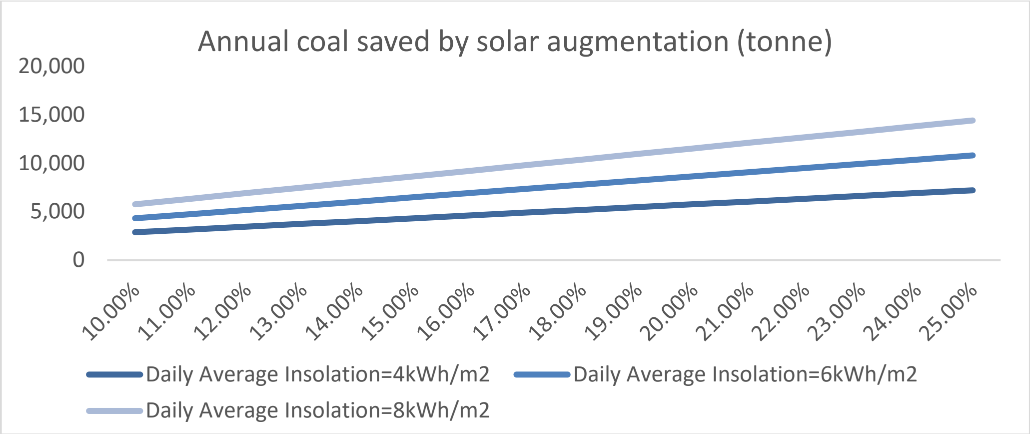
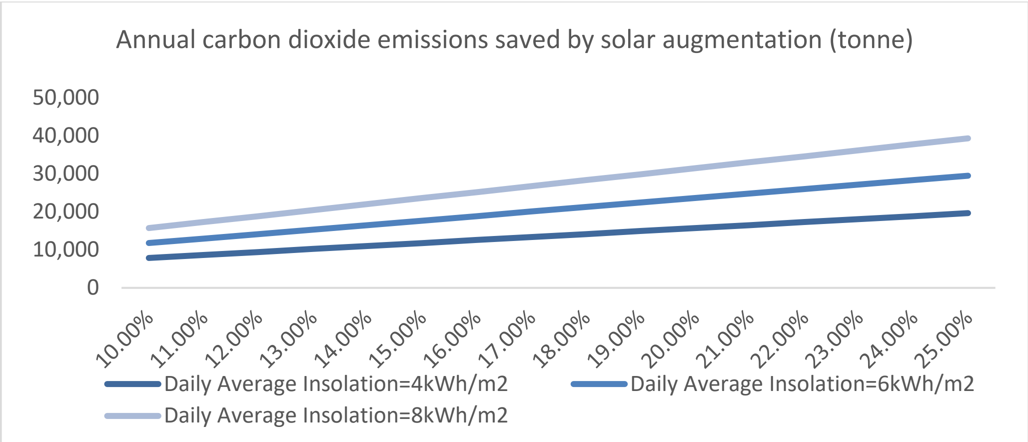


Figure 4
Annual CO_2 emissions saved by adopting solar augmentation (tonne)



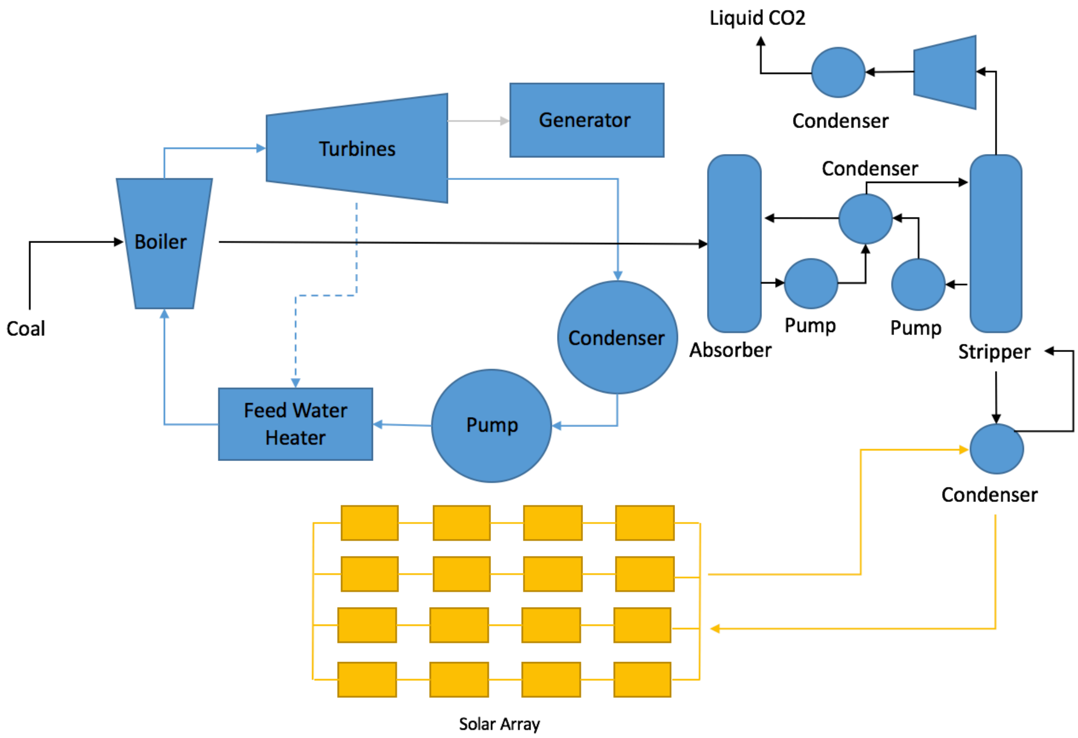
Although solar fields account for a large proportion of the total cost for a solar power generation unit, sensitivity analysis shows that the LCOE (nominal US$/kWh) of an SAPG power plant suffers less from fluctuations of solar field costs (including land and collectors) than other solar systems. This is to be expected because the SAPG requires a smaller solar collector field than other solar systems [28]. Moses Tunde Oladiran et al conducted a detailed case study on how an increase in the solar collector field influences overall thermal efficiency and therefore the LCOE [29]. When the area is small and the output of the solar system is low, the increase of area and capacity help to reduce the LCOE of the total system. After reaching the optimal point, the increase of area and capacity will lead to an increase in LCOE.

1.2. Solar aided carbon capture

In addition to solar augmentation in the Rankine cycle, efforts have been made to integrate solar into Carbon Capture and Storage (CCS) systems. It is estimated that the energy efficiency penalty of CCS for a coal fired power plant is around 8 per cent to 15 per cent [35]. To compensate this efficiency penalty, Wibberley first proposed a model of Post-Combustion-Carbon Capture and Storage using solar thermal energy in 2006 [18] as shown in Figure 5. The idea of this design is to acquire thermal energy from solar collectors instead of the original power cycle so carbon emissions can be reduced without reducing power output.

Figure 5

Model of solar aided Carbon Capture and Storage in a Rankine cycle



Wibberly's proposal of partial/total compensation of heat provided by solar thermal energy corresponds to one of the three possible modes to integrate solar into post-combustion carbon capture (PCC) discussed in [36] consists of meeting the energy requirement of reboilers with solar heat coming from a fluid or a solar collector system. Mokhtar [9] argued that providing partial energy through solar would be beneficial considering the high cost associated with the solar system needed. In their proposal, if energy from the solar system was sufficient, the system would turn on the solar system; otherwise, the turbine circuit would provide the steam.

1.2.1. Benefits and drawbacks

With energy for CO_2 capture provided by solar-generated steam, the energy penalty during solar hours will be approximately zero provided the solar plant has enough capacity. Also, this is a way to integrate solar energy without concerns about its variability since steam from the turbine is always available as an option.

The main drawbacks of solar aided CCS includes increased capital costs, land occupation and complexity of operation [36], particularly considering that solar-generated steam is likely to be used rather than solar-generated electricity given the need for steam [36]. Hence this technology is unlikely to benefit from the rapid cost reductions observed in photovoltaic (PV) technology.

1.2.2. General cost and performance estimation

For this technology, the cost of electricity (COE) and cost of CO_2 avoidance (COA) are mainly determined by local climatic conditions, namely the local solar insolation. A research study [8] comparing COE and COA of solar aided CCS power plants in Alice Springs in Australia, Beijing in China, and Denver in the US revealed that the plant in Alice Springs has lower COE and COA than the ones in Beijing or in Denver since Alice Springs has higher solar insolation and longer hours of sunshine. As with any technology, the capacity factor of the solar aided CCS system also matters. The more the solar aided CCS is dispatched, the lower its COE and COA. The COE and COA of the solar aided CCS system are also sensitive to the price of solar thermal collectors.

A summary of the conclusion of studies calculating COA based on power plants in different countries is shown in Table 5.

Table 5

Cost estimations conducted based on different power plants*

Base Power Plant studied	Location	Conclusions
300 MW pulverized coal-fired [9]	Australia	If the carbon price is zero, this integration will be feasible when the solar field price goes below US$ 100/m^2.
520 MW coal-fired [8]	Australia China US	In order to achieve lower cost of electricity and lower cost of CO_2 avoidance, the price of solar collector should be lower than US$ 150/m^2 (solar trough) and US$ 90/m^2 (vacuum tube).
600 MW coal-fired [37]	China	The COAs are 25.8 US$/ton-$CO_2$ for a simple SAPG plant and 10.8 US$/ton-$CO_2$ for a Solar-Aided-CCS plant.
300 MW coal-fired [12]	China	Solar aided post combustion CO_2 capture yields higher generation than ordinary post combustion CO_2 capture (2126 GWh and 1996 GWh), solving about 200 GWh energy penalty.

* *These results come from simulations, not from real projects.*

Part 2: Coupling wind energy with Integrated Gasification Combined Cycle (IGCC) coal plants

2.1. IGCC plants: pairing wind with Carbon Capture and Storage

An Integrated Gasification Combined Cycle (IGCC) plant allows for the use of solid and liquid fuels in a plant that has the same environmental benefits as a natural gas-fired plant [38]. To do this, the IGCC unit begins by taking the fuel and gasifying it with oxygen or air. The product of this process is called syngas (short for synthetic gas), which is cleaned of particulate matter and other harmful species such as sulphur dioxide before being fired in a gas turbine and integrated in a combined cycle. Like with all combined cycles, the hot syngas spins a turbine to generate electricity and the waste heat is used to make steam which also spins another turbine. In this way, the process uses as much energy as possible to generate electricity from two turbines, resulting in a more efficient plant design than a simple gas turbine or single-cycle thermal power plant [38].

2.1.1. Benefits and drawbacks of CCS operation in IGCC plants

When looking for ways to reduce the CO_2 intensity of a power plant, the main drawbacks of carbon capture and storage (CCS) systems are the high capital costs, the increase in operating and maintenance costs, and the energy penalty imposed due to the need for steam and electricity to operate the CCS systems. This report looks at a way to reduce this energy penalty by compensating for the energy lost with renewable energy production.

CCS systems in a traditional pulverized coal plant are located post-combustion, meaning that after the coal is burned the resulting gases would go through the CCS process. Most coal plants already incorporate flue gas desulphurization and particulate matter controls post-combustion, to limit the emissions of sulphur oxides (a precursor to acid rain) and particulate matter (a human health hazard). In these plants, a CCS system could be added post-combustion to scrub the CO_2 from the gas, most commonly done with an amine system. It is important to note that after the coal has been combusted the concentration of CO_2 in the flue gas is quite low, which is why capturing carbon post-combustion is such an energy-intensive process.

In an IGCC plant, however, the CCS system would be placed pre-combustion: capturing the CO_2 from the input stream of syngas after gasification but before combustion. The CO_2 in this input stream is at a much higher concentration than it would be in the flue gas from pulverized coal plants and hence, is easier to capture. Another advantage is that it can run on various feeds, including biomass and even natural gas. This makes an IGCC plant more flexible than a typical coal plant, and enables it to respond to supply shocks or market changes in fuel prices. However, there is limited deployment of utility-scale plants worldwide (particularly, IGCC plants running on coal), which are reviewed in the following sections.

2.1.2. Projects around the world

During the last two decades, five coal-based IGCC plants have come online in the United States and Europe: in Mississippi, Florida, and Indiana in the U.S., Buggenum in the Netherlands, and Puertollano in Spain [39], [40]. Table 6 provides an overview of the plants, with updates on their status and profitability.

Table 6
Current IGCC plants

Name	Location	Company	Description	Status	Update/Reason for Shutdown
Puertollano IGCC Plant	Puertollano Spain	ELCOGAS	300MW target project through THERMIE program, operational since 1997. Total cost US$ 555 million (1991 US$). [41]	Operational	In 2010, a CO_2 capture and H_2 production pilot plant was added to the system. The IGCC plant has also experimented with running on up to 10 per cent biomass feed, with promising results. [42]
Willem Alexander Powerplant	Buggenum, Netherlands	Nuon	$253MW_{net}$ demonstration facility, in service since 1994, commercial operation since 1998. [43]	Closed April 2013 [44]	Low energy prices in the region combined with the high-cost basis of the plant made profitable operation “impossible.” [44]
Kemper County IGCC Project	Mississippi, US	Southern	582 MW plant, carbon capture used for enhanced oil recovery [40]. Combined cycle operational since August 2014, gasification proving problematic [45]. Total costs have climbed up to US$ 7.1 billion. [46]	Commercial Operation Delayed [47]	Only competitive with natural gas if gas prices go above US$ 5/MMBTU [46]. A tubing leak has caused an indefinite delay in operation since March 2017 [47].
Polk Power Station	Florida, US	Tampa Electric	260MW ($220MW_{net}$) unit began commercial operation in 1996. [48]	Operational	Expansion completed in 2017 to change simple-cycle gas units to combined-cycle units. This is not in the IGCC unit, but the others that make part of the plant. [49]
Wabash River Coal Gasification Repowering Project	Indiana, US	Duke Energy	Retrofit of Unit 1 of a pulverized coal plant, 1995. 192MW gas turbine, 112.5MW steam turbine. Total cost 438 million, half funded by DOE. [50]	Shut down 2016, gasification unit still online [51]	New federal pollution rules push Duke Energy to cut coal power plants or retrofit them to meet stricter emissions standards. Original Wabash power plant is over 50 years old, shut down to avoid expensive pollution control. [51]

2.1.3. Planned Projects

A few coal-based IGCC plants have been planned in the ECE region, but financial and governmental issues have caused the majority of them to be stalled or discontinued. Information on planned IGCC plants in the ECE region is provided in Table 7.

Table 7
Planned IGCC projects and status

Name	Location	Company	Description	Status	Reason for cancellation/ delay in implementation
Nuon Magnum	Netherlands	Nuon	750 MW using coal, biomass, 450 MW using natural gas; partial CO_2 capture. [52]	Postponed	Rise in raw material prices and pending negotiations with environmentalists. [52]
IGCC-CCS Project in Hurth	Germany	RWE	360 MW using lignite feed; storage in depleted gas reservoirs or saline aquifers. [53]	Discontinued	German carbon storage law tightened CCS constraints, CO_2 storage deemed impossible by RWE. [53]
Teesside	UK	Centrica	800 MW using coal feed; 85 per cent CO_2 capture. [54]	On Hold	No government funding for pre-combustion CO_2 capture, not financially viable. [54]
Don Valley Power Project	UK	Powerfuel	650 MW using local coal; 90 per cent CO_2 capture. [55]	Stalled	Financial issues, expected to be in operation by 2020. [55]

2.1.4. Integration with wind for CCS

Although a coal-based IGCC requires significant energy to gasify coal, as explained earlier, a carbon capture system in an IGCC plant would use less energy than CCS in a pulverized coal plant (more details are provided in Table 8). IGCC plants could be paired with different sources of renewable energy to make up for the reduced power generation capacity without increasing air emissions. The following section focusses on wind power co-located with a CCS plant. As stated in the introduction, this makes sense only if there are high costs or difficulties to provide the necessary power generation capacity to integrate wind from geographic areas with better wind resources, or if the wind resources of the land adjacent to the CCS plant are as good as in any other place.

2.1.5. Cost Analysis: Levelized Cost of Electricity

Four approximately equal power plants were modelled using Carnegie Mellon's publicly available Integrated Environmental Control Model (IECM) to look at the costs and benefits of IGCC compared to a traditional pulverized coal plant [56]. The models assumed North Dakota lignite coal is used because this is the same coal rank as the lignite coal that is most commonly used in the European region [57]. The cost of coal in Europe is currently US$ 56.64/tonne [58]. Because net electricity output represents how much electricity a plant can deliver to the grid (gross electricity produced minus the plant's own electricity requirements), the modelled plants were designed to produce the same amount of net electricity. Note, therefore, that the pulverized coal plant's gross electricity output was modified so that the net electricity between the IGCC and PC plants match, in order to compare the technology's costs and carbon intensities for an equal amount of electricity generation for consumers. The IECM gives cost and operation results for the different plants, which can be used to determine the LCOE.

The LCOE can be simply defined as the total costs a plant will incur spread out over the product it will sell, electricity [59]. Equation 1presented in section 2.1.3, shows how the LCOE takes annualized capital costs for a plant (equal to capital costs times a capital recovery factor), variable operation/maintenance (O&M) cost, fixed O&M costs, and fuel costs to determine the total costs for the plant in a given year. These costs can then be divided by the total electricity generation that plant will produce in a year (determined by the plant's capacity and capacity factor), which gives the LCOE (here reported in US$/MWh, using constant 2014 US$).

The results for the different plants that were modelled: a pulverized coal plant with and without CCS, and an IGCC plant with and without CCS, are provided in Table 8.

Table 8.
Cost and CO_2 modelling results from IECM

Plant Type	MW Gross	MW Net	LCOE (US$/MWh)	CCS	CCS Energy Use (MW)	Cost of CO_2 Control (US$/MWh)	CO_2 emissions intensity (kg/MWh)
PC	758	690	130.33	None	0	0	952.7
IGCC	1,153	690	211.03	None	0	0	1,371.6
PC	675	515	223.05	Amine	228.78	45.06	140.6
IGCC	1,121	515	327.38	Sour Shift and Selexol	83.88	75.82	114.6

When producing the same net electricity for consumers, a basic pulverized coal plant has a lower LCOE and even a lower carbon intensity than an IGCC plant. However, when considering options for CCS, the IGCC plant's CO_2 emissions intensity can be reduced to around 115 kg/MWh whereas the equivalent pulverized coal plant's intensity would only be reduced to around 141 kg/MWh. The model results show that IGCC plants continue to be more expensive on a US$/MWh basis, but there are significant CO_2 reductions that can be achieved requiring less energy than a pulverized coal plant would need. As the table shows, a pulverized coal plant would use nearly 230 MW of energy on its amine capture system, whereas the IGCC plant would only require 84 MW for its Selexol CO_2 capture system. These energy penalties could be offset with power generation from co-located wind turbines.

Assuming turbines sized to produce 2 MW (the average size for new turbines, [60]) with a capacity factor of 0.38 (the National Renewable Energy Laboratory average for utility-scale wind, [61]), it is possible to estimate the number of wind turbines that would be needed to offset the CCS energy demand for these plants. According to the National Renewable Energy Laboratory, recent utility-scale wind projects using 2 MW turbines averaged capital costs of US$ 2.3 million/MW, with fixed O&M costs of US$ 33,000/MW-yr [62]. The average wind turbine also requires a land area of 0.345km^2/MW [63]. Using this information, the costs and the land use of building the wind capacity to offset the CCS energy demand for the coal plants can be estimated. The results of these calculations are presented in Table 9 below.

Table 9.

Wind Requirements to offset CCS energy use

Scenario	IGCC with CCS	PC with CCS
CCS Energy Use (MW)	83.88	228.78
Number of Turbines	89	241
Land Use (km^2)	61.41	166.29
Total Cost Wind (US$MM/yr)	39.38	106.64
Original LCOE (US$/MWh)	327.38	223.05
New LCOE (US$/MWh)	290.6	174.9
Land Use Intensity (km^2/ΔLCOE)	-1.67	-3.45

The levelized costs above show how much the LCOE for the initial plants would change if a wind farm was built to meet the CCS energy demand of the original plant. This LCOE is calculated as described in Equation 2:

Equation 2. Calculation of Levelized Costs of Electricity for the Initial Plants Would Change If a Wind Farm Was Built To Meet The CCS Energy Demand

$$LCOE = \frac{CapEx_{Coal} + O\&M_{Coal} + Fuel_{Coal} + CapEx_{Wind} + O\&M_{Wind}}{Generation_{Coal} + Generation_{Wind}}$$

Note how the denominator spreads the costs out over the total amount of electricity being produced from both the coal plant and the wind farm. Because the wind farm makes up for the energy the plant would lose by installing a CCS system, the original power plant effectively has more energy that it can sell to its consumers even though it is now capturing its emissions. The wind farm doesn’t add much to the capital and operating costs of the original plant, which is why we see an overall decrease in the LCOE for the plant were it to offset its energy penalty using wind rather than simply accepting the loss in energy production for CCS purposes. This also provides a benefit for wind power, as some of the highest costs incurred for wind come from integrating these resources to the electric grid and accounting for the variability and uncertainty in the wind forecast. By not integrating the wind farm directly to the grid but rather combining it with a coal power plant, these integration costs can be avoided as the power plant uses the wind energy directly instead of trying to dispatch it out to the grid.

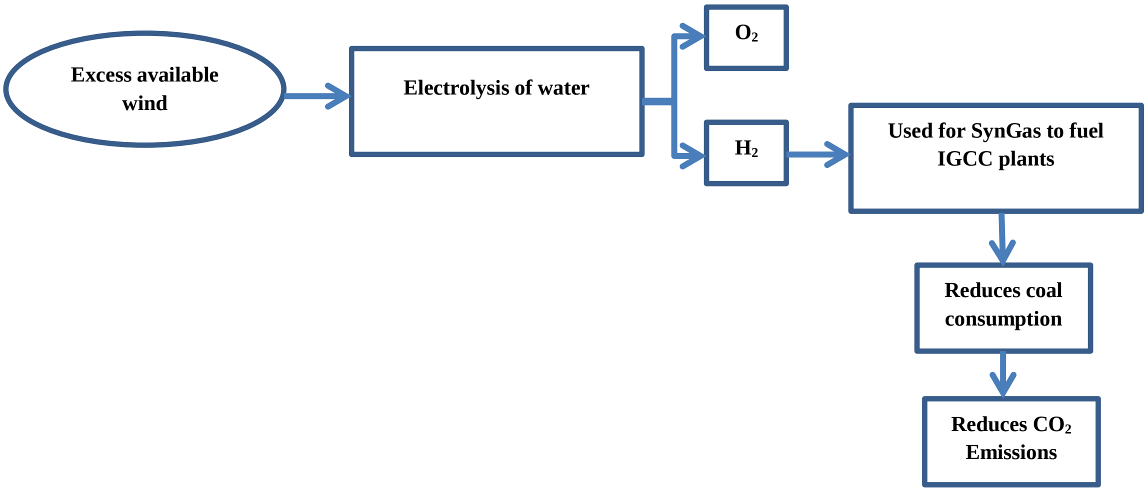
While it seems that the LCOE for the pulverized coal plant combination continues to be lower than that of the IGCC plant combination, for countries with limited land availability it is also important to consider the land use of the wind farms that would help these power plants achieve these cost levels. The "land use intensity" metric was developed to see what the land requirement is for each unit decrease in the LCOE of the original plant with a CCS system. In other words, it provides a way to measure how much land is required for a power plant to decrease its LCOE after installing a CCS system. Because the energy intensity of CCS in an IGCC plant is much lower than the energy requirements for CCS in a traditional pulverized coal plant, the turbine needs are also much lower. As a result, an IGCC plant has a land use intensity of 1.67km^2 per US$/MWh decrease in costs, whereas the pulverized coal plant has a land use intensity of 3.45km^2 per US$/MWh decrease in costs. In other words, the same reduction in electricity cost (US$/MWh) can be achieved with about half the land use for an IGCC plant than it would take for a pulverized coal plant—however, since the IGCC plant starts at a higher LCOE these land use effects aren't as clearly represented by the final LCOE calculations. To determine the best use of land, mapping software can be used to find sites for pairing IGCC or pulverized coal plants with wind and CCS.

2.2. Water Electrolytic Hydrogen Production

The total wind or solar based electricity available at a given time instant is not always dispatched to the grid because of constraints on the capacity of transmission lines, lack of operational flexibility in the power system where it operates, or insufficient demand. To still take advantage of the low cost and zero carbon power that could potentially be generated with wind, it is possible to use it to generate hydrogen for sale or for the production of syngas that can be injected into a natural gas pipeline or combusted in a power plant (NGCC, CC or IGCC) to generate electricity [64]. The oxygen produced as a by-product of electrolysis can also be sold to chemical industries, or can be used in oxyfuel combustion [65] power plants.

Figure 6

Operation of water electrolytic hydrogen production that couples wind with coal



Older studies on water electrolytic hydrogen production with solar and wind indicate higher production costs for the use of solar PV compared to wind power [66]. However, given advances in developing cheap solar PV technologies, more recent analysis [67] indicates that the overall cost of water-electrolytic hydrogenation from renewable resources depends upon the renewable power potential in regional, and in some cases the associated costs using solar PV may be cheaper than wind.

Traditionally IGCC plants use a coal-based chemical reaction (or a mixture of coal and biomass) to generate hydrogen to be used in its combustion turbines. The literature [64] [68] indicates that up to 49 per cent of the coal requirements for producing hydrogen could be economically reduced by using wind power for water electrolytic hydrogen production, thereby causing reductions in CO_2 emissions from the IGCC plant by up to 57 per cent [68]. In addition, the IGCC plant may also be designed to incorporate Carbon Capture and Storage, resulting in further reduction in CO_2 emissions by 98-99 per cent [5].

The oxygen generated as a byproduct of electrolysis may be sold to chemical factories or be purified further and be used for oxy-fuel combustion [64]. Note that a similar procedure could be performed with biomass as the only source of carbon [69]. Table 10 provides an overview of pilot projects being implemented by different organizations to demonstrate this technology:

Table 10.
Pilot projects for water electrolytic hydrogen production to couple wind with IGCC plant operation

Brief Description of Project	Country	Organization	Status of Project
Water electrolytic hydrogen production by wind power applied to IGCC plants with CCS, co-fired by coal and biomass [70]	USA	National Energy Technology Laboratory (NETL)	Research and Development Phase
Water electrolytic hydrogen production by wind power applied to IGCC plants fired by coal. [71]	USA	Leighty Foundation	Conceptual models and simulations
Water electrolytic hydrogen production by wind power applied to IGCC plants co-fired by coal and biomass [72].	New Zealand	CRL Energy	Small pilot scale system exists for co-fired IGCC with coal and biomass. Future steps outlined in the report indicated the need to build and study the performance of co-fired IGCC and hydrogen obtained from electrolysis of water by wind power
Water electrolytic hydrogen production by wind power applied to IGCC plants co-fired by coal [73]	Germany	Siemens	Development of a pilot project is one of the primary goals. As of now, projects on water electrolytic hydrogen with high efficiency has been developed.
Water electrolytic hydrogen production by wind or solar power applied to IGCC plants co-fired by coal [74]	China	Siemens	Ongoing work on use of H_2 obtained from electrolysis of water by wind or solar, in IGCC plant operation

The primary advantage of using renewables for hydrolysis is mainly that it provides an effective solution to intermittency and uncertainty of wind and solar power and to the challenges of transmitting these power from remote locations. Stand-alone wind or utility-scale solar farms isolated from the grid may be used to generate hydrogen for direct use or for generating syngas (for combustion in power plants or for other uses) if there is the proper storage and transportation infrastructure. Similarly, additional revenues may be earned if there is the proper market for the oxygen produced as a by-product of electrolysis.

The primary barriers to widespread deployment of water electrolytic hydrogen production to couple wind and coal include its high capital costs and the low efficiency of the electrolysis procedure. Current capital costs of installation of hydrolysis systems are much higher than those of conventional power plants indicating the need for further improvements in efficiency to lower costs. Similarly, the energy requirements to electrolyze water are still high.

2.2.1. Cost considerations

At present, conceptual models of power plants used to estimate the LCOE produced by coupling wind with IGCC plants using water electrolytic hydrogenation indicates values in the range of 15-35 cents/kWh [75]. This is more than twice the LCOE for conventional IGCC plants of ~7.72 cents/kWh, where the cost of coal is assumed to be 2.94 US$/MBtu [76]. The increase in LCOE value relative to Pulverized Coal (PC) (~5.92 cents/kWh) (cost of coal assumed to be 2.94 US$/MBtu) and Natural Gas Combined Cycle (NGCC) plants (~5.89 cents/kWh) (cost of natural gas assumed to be 13.5 US$/MBtu) is even higher. However, studies indicate that considerable reductions in cost of production in the range of 3.1-3.45 US$/MmBtu [77] (which corresponds to reduction in LCOE values in the range of 11.20-12.50 cents/kWh) when the by-products of electricity production in IGCC plant are used to produce ammonia in co-located chemical plants.

The H_2 produced from wind-based electrolysis of water can be stored for use during peak load or periods of high electricity demand. Thus, this technology may also be considered as a storage device rather than a conventional source of electricity. Under such considerations, in 2009, NETL found that the levelized cost of generating electricity in IGCC from hydrogen produced by wind-based water electrolysis would be much lower than that of nickel-cadmium (Ni-Cd) and sodium-sulphur (NaS) and Vanadium redox batteries and only slightly higher than pumped hydro or compressed air energy storage (CAES) systems [75]. Cost of generating electricity in IGCC from hydrogen produced by wind-based water electrolysis is also comparable to that of lithium-ion batteries [59] where cost of storage varies between 28-58 cents/MWh for peaking power plant replacements.

Since most of these cost estimates are based on conceptual modelling rather than industrial scale units, it may be possible to obtain additional reductions in cost due to economies of scale [78]. However, it is also possible that the risks of storing and handling hydrogen grow proportional with scale, and hence the costs of taking proper precautions may offset any benefits [79].

Part 3: Conclusions

This publication presents an overview of different approaches to coordinated operation of coal fired and renewable electric power plants. It is evident that while technical designs for coordinated operation of coal units with renewable sources of electric power provide alternate pathways to renewable power integration, economic feasibility and a comprehensive policy structure is crucial for actual implementation of these technologies. One of the primary reasons why the deployment of low carbon technologies such as these are difficult, is because of insufficient financial incentives to invest in reduction of CO_2 emissions from existing power plants. In a given region, proper organization of available data and thorough research is also necessary for identification of suitable renewable resources to be coupled with coal to ensure economic and reliable coordinated operation of coal-fired power plants with renewable energy plants.

The case for replacing the lost power generation capacity of a coal-fired plant due to CCS by co-locating a wind plant is harder to make than the case for colocation of a thermal solar plant. This is because while a thermal solar plant produces steam that can be integrated directly into the power plant, a wind farm generates electricity that could or not be generated in situ. After all, installing wind power plants in the regions with best wind resources and ensuring the proper power transmission capacity is in place, is a way of coordinating the operation of CCS with renewables. However, because of the lack of power transmission capacity, and the high costs and difficulties of making it available, it is worth exploring the potential of co-locating fossil fuel-fired power plants with CCS, with wind power.

The scope of implementation of such technologies within the ECE region is provided as a conclusion to this publication,

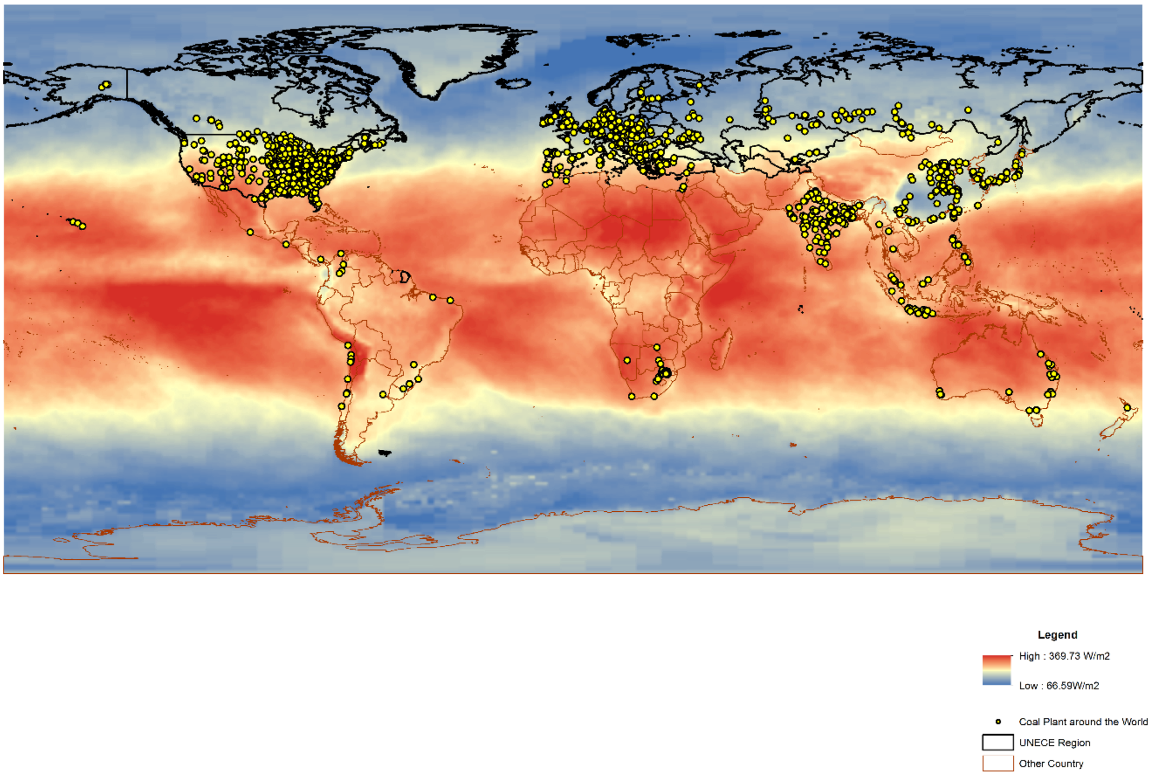
3.1. Scope of implementation of coordinated operation of solar thermal technologies with coal

The solar insolation in the ECE region is illustrated in Figure 7. January, April, July and October have been selected as sample months and average insolation data for these four months is obtained through NASA. Figure 6 presents the average insolation of the typical four months, which is an estimation of average insolation during a year.

As can be observed, the majority of the ECE region is located in the northern hemisphere at relatively high latitude. The average insolation most of the territory is lower than 240 W/m^2. Southern United States, especially the southwest, is promising in terms of solar thermal energy development.

A more detailed analysis of the characteristics of total daily insulation is required to which specific areas are suitable for developing solar aided power generation. According to a report from NREL [21], to be considered for the development of a solar aided project, the average total daily insolation observed in a geographic area should be greater than 4 kWh/m^2. Since the hours of day light in the ECE region have not been identified, it is difficult to assess which coal plants are located in areas that exceed this threshold.

Figure 7
Solar insolation in the ECE region



3.2. Scope of implementation of coordinated operation of wind technologies with coal

Table 11 , provides a ranking of the countries in the ECE region that are responsible for the largest percentage of overall coal-fired electricity generation in the region. These countries combined account for nearly 93 per cent of the coal generation in the ECE region (when excluding the U.S., nearly 38 per cent is accounted for). Because they have the most coal generation in the region, they also have the most potential for the use of carbon capture for emissions reductions. The following sections consider a few cases for implementation of CCS and wind: EU member countries, Russian Federation, Canada, and the U.S. These cases provide a basis for how the ECE region would benefit from coupling these technologies with existing and new coal plants, whether they be IGCC or pulverized coal.

Table 11
Top countries generating coal-based electricity in the UNECE region

Rank	**Country**	**Number of Coal Plants** [80]	**Annual Coal Generation (GWh)** [81] [82]	**Percent of ECE Coal Generation** [81] [82]

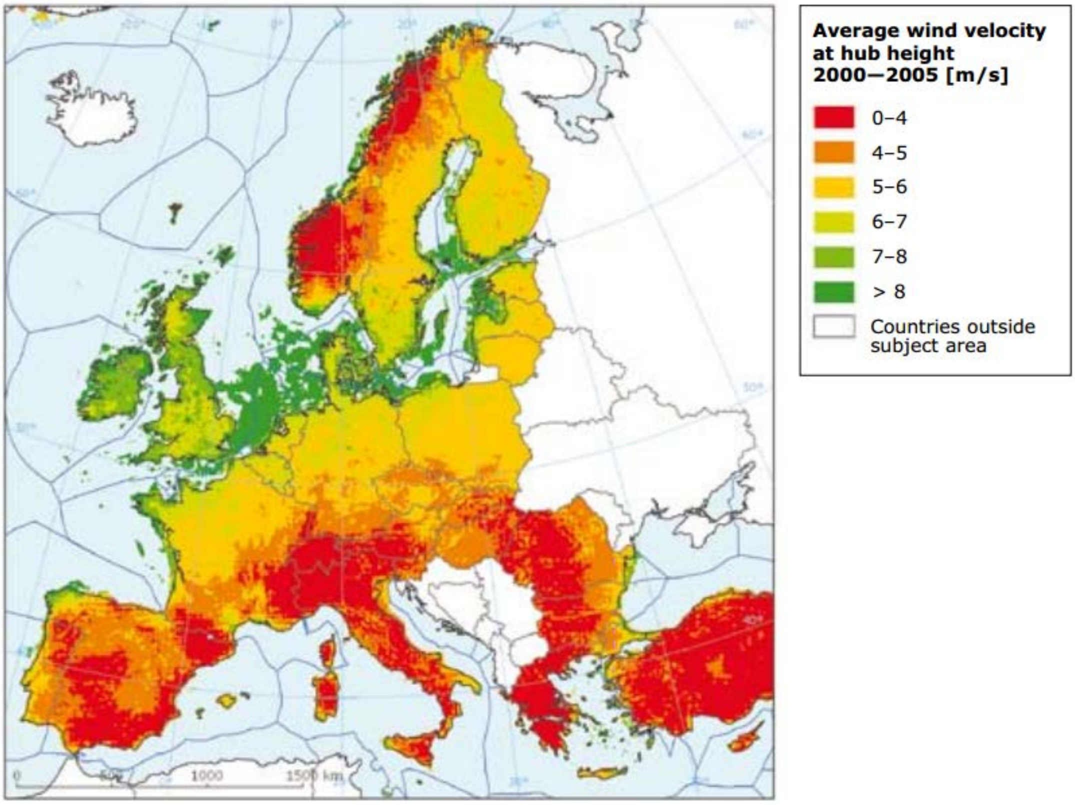
1	United States of America	524	1,637,097	54.9
2	Germany	47	276,588	9.3
3	Russian Federation	48	161,728	5.4
4	Poland	39	127,800	4.3
5	United Kingdom	18	123,950	4.2
6	Kazakhstan	14	80,487	2.7
7	Ukraine	14	71,478	2.4
8	Canada	16	63,300	2.1
8	Turkey	16	63,574	2.1
10	Italy	10	44,856	1.5
11	Czech Republic	15	41,120	1.4
12	Spain	19	40,128	1.3
13	Israel	2	30,495	1.0
	TOTAL	782	2,762,601	92.6

3.2.1. 2030 Climate & Energy Framework

Twenty-eight of the fifty-six ECE member states are also members of the European Union (EU), with five more countries in the process of integrating EU legislation to join the Union [83]. These countries have adopted energy and carbon reduction strategies through the European Commission’s 2030 Climate & Energy Framework, which builds on the 2020 Climate and Energy Package and aims to make significant progress towards the targets set for the Paris Climate Accords as well as the EU’s own “2050 Low Carbon Economy” goals [84] [85]. The 2030 goals are threefold: achieve a minimum 40 per cent cut in greenhouse gas emissions (relative to 1990 levels), a minimum 27 per cent share for renewable energy, and a minimum 27 per cent improvement in energy efficiency [84]. Pairing coal plants with wind energy for CCS in this region would help address two of these goals simultaneously: reducing GHG emissions and increasing renewable energy use. Adding CCS systems to coal plants in general would help decrease their GHG emissions, but doing these retrofits would come with an energy penalty as previously discussed. This is where the incorporation of wind energy becomes beneficial, making up for the lost energy used for the CCS system by producing more energy from a renewable source.

Of these thirty-three countries (including those that are in the process of transitioning into the EU), seven are on the list presented in Table 11 of the top coal-generating countries. Germany, Poland, the United Kingdom, Turkey, Italy, Czech Republic, and Spain together account for 24.1 per cent of the coal-based electricity generation in the UNECE region, and these countries should be working towards the EU 2030 framework goals (save the UK, expected to complete its EU exit in 2019). Figure 8. below shows the wind power potential in Europe, where countries with high wind potential (5-6 m/s and above) can be identified. These countries would easily be able to pair CCS with wind power in order to reduce emissions.

Figure 8
Average wind velocity at 80 metres height



Source: European Environment Agency, 2009 [25]

3.2.2. Reductions from the Russian Federation

The Russian Federation alone accounts for 5.4 per cent of ECE coal-fired electricity, making it the third largest user with high potential for incorporation of CCS to reduce GHG emissions. Whilst the Russian Federation is the world's third largest emitter of greenhouse gases [86], the country has set goals to cut emissions by 30 per cent by 2030 [87]. One way in which the country plans to reduce the carbon intensity of the electricity sector is by replacing oil generation with wind power [88]. This initiative was proposed in the Russian parliament in late 2016, and it indicates that the Russian Federation has much untapped wind power that it could harness [88]. With the Russia Federation's reductions targets and wind potential, coupling CCS systems in existing coal plants with wind power would be another way to reduce emissions while increasing renewable penetration. This retrofit option make it more economic implementing to implement amine-storage in post combustion systems [89]. Table 12 presents the results of IECM modelling done to illustrate this point, assuming a coal plant whose capital costs have already been paid off, and assuming the retrofit capital cost penalty, relative to a new plant installation is negligible.

Table 12
Pulverized coal plant with CCS and wind

Category	Characteristic	Value
Coal Plant	Gross Capacity (MW)	758
	Net Capacity (MW)	578.7
	CCS Energy Penalty (MW)	256.9
Turbines	Number Needed	271
	Land Use (km^2)	186.99
	Total Cost (MUS$/yr)	119.92
LCOE	Before CCS (US$/MWh)	96.36
	After CCS (US$/MWh)	155.24
	After CCS + Wind (US$/MWh)	99.95

**Retrofit Modelling Results from IECM*

As Table 12 "Pulverized coal plant with CCS and wind" shows, retrofitting a coal plant with a CCS system alone would increase the LCOE by over 60 per cent, but by combining a CCS retrofit with the addition of a wind system to balance the energy penalty, the LCOE of the original plant only increases by 3.7 per cent. Coupling the CCS system with wind would be a cost-effective way for Russia to reduce emissions from its existing coal plants while harnessing wind power to keep electricity costs down.

3.2.3. Canada's 2030 Climate Targets

Canada is another country on the list of the top contributors to coal-fired electricity in the ECE region. The country has set a 2030 carbon reduction target to reduce emissions to 30 per cent below 2005 levels, but projections from Environment Canada show that they are not on track to meet these goals [90]. Canada's current electricity mix is about 75 per cent emissions-free, using mostly hydroelectric, nuclear, and renewable sources [90]. In order to meet the 2030 climate targets, a complete decarbonization of the electric grid would be necessary [90], meaning that existing coal plants would either need to be shut down or equipped with CCS systems. As was discussed for the Russian Federation and presented in Table 12, retrofits for existing pulverized coal plants become more economic when coupled with wind systems. A map issued by the Canadian Geographic and the Canadian Wind Energy Association in 2009 shows that many parts of Canada have high wind potential, which could be cross-referenced with current coal plants to determine where wind-coupled CCS retrofits could be made [91]. This map could also be used to consider the siting of new IGCC plants equipped with CCS systems and paired with wind farms that the _Government could invest in.

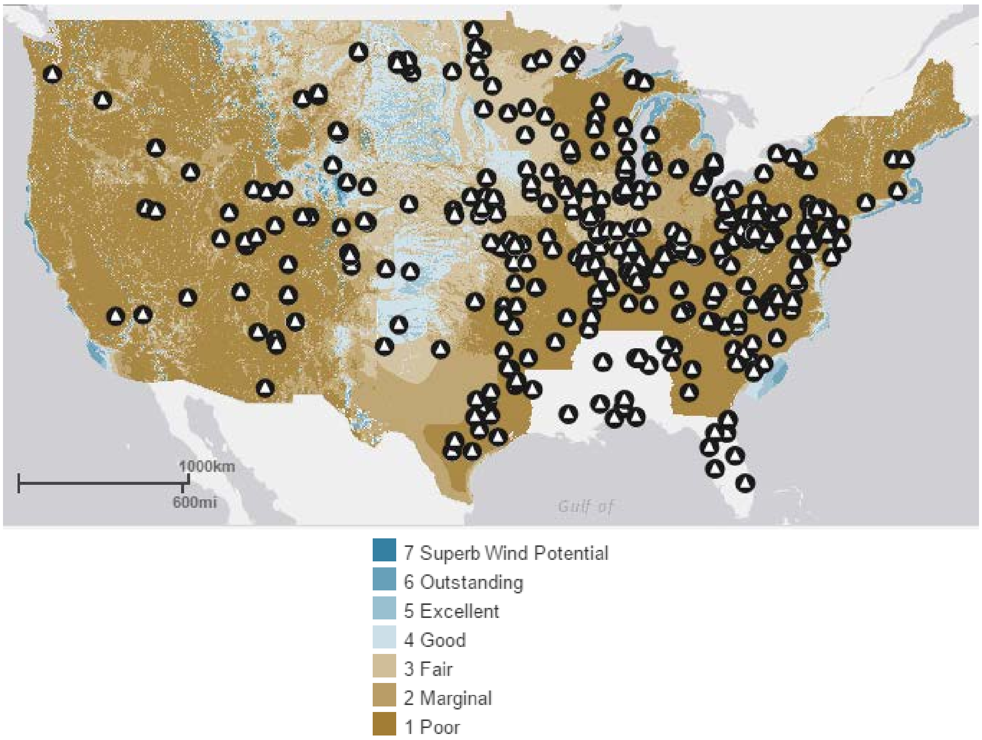
3.2.4. Potential for CCS and wind coupling in the United States

The United States alone accounts for more than half of the coal-fired generation in the ECE region, and it is the second largest emitter of GHGs in the world (following China). Before President Trump's withdrawal from the Paris Agreement, the United States' commitment was to reduce emissions by

26-28 per cent below 2005 levels by 2025 [92]. This was expected to be done through the Climate Action Plan introduced by the Obama Administration and the Clean Power Plan, but the Trump Administration has announced a desire to eliminate the Climate Action Plan and the Clean Power Plan while also investing more into reviving coal in the U.S [92].

One possibility for the U.S. could be to invest in new IGCC projects to continue using coal, but couple these with CCS and wind as described earlier in order to reduce emissions without sacrificing electricity output. Figure 9 shows the wind potential in the U.S. as well as current coal plants. This map could help pinpoint which locations have the most wind potential to couple with new IGCC plants, while also pointing out current coal plants located in wind-heavy areas that could be cheaply retrofitted (as shown in Table 12.) to reduce emissions. These options could perhaps present a compromise for the U.S.: continuing to invest in coal while also reducing emissions and increasing renewables in order to help meet its reduction targets.

Figure 9.
US Coal Plants and Wind Potential at 50 Meters Height



SOURCE: Energy Information Administration (Wind 2014, Coal 2017). [93]

Bibliography

[1] International Energy Agency, "Resources to Reserves 2013," 2013. [Online]. Available: http://www.iea.org/publications/freepublications/publication/Resources2013.pdf. [Accessed 16 December 2016].

[2] B.P., LLC, "BP Statistical Review of World Energy June 2016," June 2016. [Online]. Available: https://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2016/bp-statistical-review-of-world-energy-2016-full-report.pdf. [Accessed 16 December 2016].

[3] US Energy Information Agency, "International Energy Outlook 2016," May 2016. [Online]. Available: http://www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf. [Accessed 2016 December 2016].

[4] Internation Energy Agency, "World Energy Outlook 2016 sees broad transformations in the global energy landscape," 2017. [Online]. Available: https://www.iea.org/newsroom/news/2016/november/world-energy-outlook-2016.html. [Accessed 09 08 2017].

[5] Electric Power Research Institute, "Electric Power System Flexibility: Challenges and Opportunities," 2016.

[6] J. Davison, "Electricity systems with near-zero emissions of CO2 based on wind energy and coal gasification with CCS and hydrogen storage," *International Journal of Greenhouse Gas Control,* vol. 3, p. 683–692, 2009.

[7] Eurelectric, "Flexible Generation: Backing Up Renewables," 2011.

[8] J. Cochran, D. Lew and N. Kumar, "Flexible Coal: Evolution from Baseload to Peaking Plant," [Online]. Available: http://www.nrel.gov/docs/fy14osti/60575.pdf. [Accessed 16 December 2016].

[9] H. Li, J. Yan and P. Campana, "Feasibility of integrating solar energy into a power plant with amine-based chemical absorption for CO2 capture," *nternational Journal of Greenhouse Gas Control,* vol. 9, pp. 272-280, 2012.

[10] M. Mokhtar, M. T. Ali, R. Khalilpour, A. Abbas, N. Shah, A. A. Hajaj, P. Armstrong, M. Chiesa and Sgouris Sgouridis, "Solar assisted post-combustion carbon capture feasibility study.," *Applied Energy,* no. 92, pp. 669-676, 2012.

[11] T. Williams and H. W. Price, "Solar Thermal Electric Hybridization Issues," 1995.

[12] M. Petrov and T. Fransson, "Solar Augmentation of Conventional Steam Plants: from System Studies to Reality," in *World Renewable Energy Forum*, Denvor, 2012.

[13] R. Zhai, Y. Zhu and D. Chen, "The Evaluation of Solar Contribution in Solar Aided Coal-Fired Power Plant," *International Journal of Photoenergy,* 2013.

[14] L. Griffith, "Solar Fossil Hybrid System Analysis: Performance and Economics," *Solar Energy,* vol. 33, no. 3-4, pp. 265-276, 1984.

[15] S. F. W. R. J. Zoschak, "Studies of the direct input of solar energy to a fossil fueled central station steam power plant," *Solar Energy,* vol. 17, no. 5, pp. 297-305, November 1975.

[16] E. Hu, A. Nishimura, F. Yilmaz and A. Kouzani, "Solar Thermal Aided Power Generation," *Applied Energy,* vol. 87, 2010.

[17] Q. Yan, Y. Yang, A. Nishimura, A. Kouzani and E. Hu, "Multi-point and Multi-level Solar Integration into a Conventional Coal-Fired Power Plant," *Energy and Fuels,* vol. 24, no. 7, pp. 3733-3738, 2010.

[18] E. H. You Ying, "Thermodynamic advantages of using solar energy in the regenerative Rankine power plant," *Applied Thermal Engineering,* vol. 19, no. 11, pp. 1173-1180, 1999.

[19] L. Wibberley, "CO2 capture using solar thermal energy," 2010.

[20] H. Hong, "Proposed Partial Repowering of a Coal-Fired Power Plant Using Low-Grade Solar Thermal Energy".

[21] T. Roos, "Solar Thermal Augmentation of Coal-fired Power Stations".

[22] C. Turchi, R. Bedilion and C. Libby, "Solar Augment Potential of U.S. Fossil fuel-fired Power Plants," 2011.

[23] A. Vir., "Solar Booster Augmentation for Existing Coal Fired Power Plants".

[24] National Renewable Energy Laboratory, "Colorado Integrated Solar Project," [Online]. Available: https://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=75. [Accessed: 07-Mar-2017]..

[25] National Renewable Energy Laboratory, "Concentrating Solar Power Projects - Kogan Creek Solar Boost | Concentrating Solar Power," [Online]. Available: https://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=243. [Accessed: 07-Mar-2017]..

[26] National Renewable Energy Laboratory, "Concentrating Solar Power Projects - Liddell Power Station | Concentrating Solar Power," [Online]. Available: https://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=269. [Accessed: 07-Mar-2017]..

[27] C. Tsechelidou and G. C. Bakos, "Solar aided power generation of a 300 MW lignite fired power plant combined with line-focus parabolic trough collectors field," *Renewable Energy,* vol. 60, pp. 540-547, 2013.

[28] T. N and G. K, "An analysis of photovoltaic irrigation system for olive orchards in Greece," in *20th Innovative Manufacturing Engineering and Energy Conference*, Koila Kozani, 2016.

[29] "Simple Levelized Cost of Energy (LCOE) Calculator Documentation".

[30] "Cost and Performance Data for Power Generation Technologies," 2012.

[31] Environmental Protection Agency, "Emissions & Generation Resource Integrated Database (eGRID," 2017.

[32] International Energy Agency, "Technology Roadmap: Solar Thermal Electricity 2014".

[33] A. S. D. C. National Aeronautics and Space Administration, "NASA Surface meteorology and Solar Energy - Location".

[34] Z. Li, "Integrating solar Organic Rankine Cycle into a coal-fired power plant," *International Journal of Greenhouse Gas Control,* vol. 31, pp. 77-86, Oct 2014.

[35] "Assessment of Solar-Coal Hybrid Electricity Power Generating Systems," *Power and Energy System,* 2010.

[36] K. Goto, K. Yogo and T. Higashii, "A review of efficiency penalty in a coal-fired power plant with post-combustion CO2 capture," *Applied Energy,* vol. 111, pp. 710-710, 2013.

[37] F. Parvareh, M. Sharma, A. Qadir, D. Milani, R. Khalilpoura, M. Chiesa and A. Abbas, "Integration of solar energy in coal-fired power plants retrofitted with carbon capture," *Renewable and Sustainable Energy Reviews,* vol. 38, 2014.

[38] Y. Zhao, H. Hong, X. Zhang and H. Jin, "Integrating mid-temperature solar heat and post-combustion CO2-capture in a coal-fired power plant," *Solar Energy,* vol. 86, no. 11, pp. 3196-3204, 2012.

[39] N. A. Holt, "Integrated Gasification Combined Cycle Power Plants," 2001. [Online]. Available: https://sequestration.mit.edu/pdf/Integrated%20Gasification%20Combined%20Cycle%20Power%20Plants.pdf. [Accessed 04 08 2017].

[40] National Energy Technology Laboratory, "IGCC PROJECT EXAMPLES," 9 February 2007. [Online]. Available: https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/project-examples. [Accessed 4 8 2017].

[41] S. Patel, "Kemper County IGCC Plant Generates First Syngas-Fueled Power," 13 10 2016. [Online]. Available: http://www.powermag.com/kemper-county-igcc-plant-generates-first-syngas-fueled-power/. [Accessed 04 08 2017].

[42] National Technology Laboratory, "ELCOGAS PUERTOLLANO IGCC PLANT," [Online]. Available: https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/elcogas. [Accessed 04 08 2017].

[43] P. C. Llano and F. G. Peña, "An alternative to landfills," 16 7 2015. [Online]. Available: http://www.interempresas.net/Quimica/Articulos/141726-Una-alternativa-a-los-vertederos.html. [Accessed 4 8 2017].

[44] National Energy Technology Laboratory, "Nuon Power Buggenum IGCC Plant," 09 02 2007. [Online]. Available: https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/nuon. [Accessed 04 08 2017].

[45] "Nuon to close 253 MW Dutch coal-fired gasification plant on 1 April," 01 04 2013. [Online]. Available: http://www.conbio.info/post/nuon-to-close-253-mw-dutch-coal-fired-gasification-plant-on-1-april/. [Accessed 04 08 2017].

[46] D. Wagman, "Kemper County and the Perils of Clean Coal Technology," 28 02 2017. [Online]. Available: http://spectrum.ieee.org/energywise/energy/fossil-fuels/kemper-county-and-the-perils-of-clean-coal-technology. [Accessed 04 08 2017].

[47] Power Engineering, "Analysis Suggests Kemper County Will Not be Cost Efficient," 23 02 2017. [Online]. Available: http://www.power-eng.com/articles/2017/02/analysis-suggests-kemper-county-facility-to-be-more-expensive-than-gas.html. [Accessed 04 08 2017].

[48] Power Engineering, "Tubing Leak Causes Indefinite Delay at Kemper County," 17 03 2017. [Online]. Available: http://www.power-eng.com/articles/2017/03/tubing-leak-causes-indefinite-delay-at-kemper-county.html. [Accessed 04 08 2017].

[49] "Polk Power Station," 14 03 2017. [Online]. Available: http://www.tampaelectric.com/company/ourpowersystem/powergeneration/polk/. [Accessed 04 08 2017].

[50] "Tampa Electric completes expansion of Polk Power Station.," 14 03 2017. [Online]. Available: http://www.tampaelectric.com/company/mediacenter/article/index.cfm?article=894. [Accessed 04 08 2017].

[51] National Energy Technology Laboratory, "Wabash River Coal Gasification Repowering Project," 09 02 2008. [Online]. Available: https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/wabash. [Accessed 04 08 0217].

[52] A. Ropeik, "Duke Energy Shuts Down Wabash River Generating Station," 14 03 2016. [Online]. Available: http://indianapublicmedia.org/news/duke-energy-shuts-wabash-river-generating-station-97130/. [Accessed 04 08 2017].

[53] "Nuon Magnum IGCC power Plant, Netherlands.," 09 02 2011. [Online]. Available: http://www.power-technology.com/projects/nuonmagnum-igcc/. [Accessed 04 08 2017].

[54] K. J. Wolf, "IGCC/CCS power plant," 09 02 2006. [Online]. Available: http://www.rwe.com/web/cms/en/2688/rwe/innovation/power-generation/fossil fuel-fired-power-plants/igcc-ccs-power-plant/. [Accessed 04 08 2017].

[55] T. Macalister, "Centrica plans cleanest coal power plant in UK," 09 02 2006. [Online]. Available: https://www.theguardian.com/business/2006/nov/09/utilities.greenpolitics. [Accessed 04 08 2017].

[56] Power Technology, "Don Valley Power Project, Yorkshire, United Kingdom," 09 02 2012. [Online]. Available: http://www.power-technology.com/projects/don-valley-power-project/. [Accessed 04 08 2017].

[57] Department of Engineering & Public Policy, Carnegie Mellon University, "Integrated Environmental Control Model," 2017.

[58] EuroStat, "Coal consumption statistics," 13 04 2016. [Online]. Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Coal_consumption_statistics. [Accessed 04 08 2017].

[59] British Petroleum, "Coal Price," 21 02 2017. [Online]. Available: https://www.quandl.com/data/BP/COAL_PRICES-Coal-Prices. [Accessed 04 08 2017].

[60] Lazard, "Lazard's Levelized Cost Of Storage Analysis - Version 1.0," December 2016. [Online]. Available: https://www.lazard.com/media/438042/lazard-levelized-cost-of-storage-v20.pdf. [Accessed 14 June 2017].

[61] Windustry, "How much do wind turbines cost?," 21 02 2017. [Online]. Available: http://www.windustry.org/how_much_do_wind_turbines_cost. [Accessed 04 08 2017].

[62] National Renewable Energy Laboratory, "Utility-Scale Energy Technology Capacity Factors.," 21 02 2016. [Online]. Available: http://www.nrel.gov/analysis/tech_cap_factor.html. [Accessed 04 08 2017].

[63] National Renewable Energy Laboratory, "Distributed Generation Renewable Energy Estimate of Costs," 21 02 2016. [Online]. Available: http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html. [Accessed 04 08 2017].

[64] P. Denholm, M. Hand, M. Jackson and S. Ong, "Land-Use Requirements of," National Renewable Energy Laboratory, 2009.

[65] W. Gu and Z. Yan, "Research on the Wind/Coal Multi-Energy System," *Conference Proceedings of World Non-Grid-Connected Wind Power and Energy Conference,* pp. 1-4, 2009.

[66] T. Wall, Y. Liu, C. Spero, L. Elliott, S. Khare, R. Rathnam, F. Zeenathal, B. Moghtaderi, B. Buhre, C. Sheng and R. Gupta, "An overview on oxyfuel coal combustion—state of the art research and technology development," *Chemical engineering research and design,* vol. 87, no. 8, pp. 1003-1016, 2009.

[67] L. M. Gandia, G. Arzamedi and D. P. M, Renewable Hydrogen Technologies: Production, Purification, Storage, Applications and Safety, Elsevier, 2013.

[68] W. Davis and M. Mariano, "Optimal year-round operation for methane production from CO2 and water using wind and/or solar energy," *Journal of Cleaner Production,* vol. 80, pp. 252-261, 2014.

[69] C. Li, G. Wu, J. Li and T. Hao, "Study on the environmental impact assessment of the wind/coal multi-energy integration system," *Proceedings of World Non-Grid-Connected Wind Power and Energy Conference,* pp. 1-4, 2009.

[70] S. Mills, "The Energy Frontier of Combining Coal and Renewable Energy Systems," *CornerStone,* vol. 2, no. 4, pp. 5-10, 2014.

[71] S. Dillich, "Electrolytic Hydrogen Production Workshop," 2014. [Online]. Available: http://energy.gov/sites/prod/files/2014/08/f18/fcto_2014_electrolytic_h2_wkshp_dillich1.pdf. [Accessed 9 June 2015].

[72] B. Leighty and J. Holbrook, "Transmission and Firming of GW-Scale Wind Energy via Hydrogen and Ammonia," *WIND ENGINEERING,* vol. 32, no. 1, pp. 45-65, 2008.

[73] R. S. Whitney, T. P. Levi and A. I. Gardiner, "A Technology Package Utilising Coal, Biomass and Intermittent Renewable Electricity," *5th International Conference on Clean Coal Technologies, Zaragoza, Spain,* 12 2011.

[74] C. Buck and S. Webel, "Hydrogen from Electrolysis: The Most Versatile Fuel," 2014. [Online]. Available: http://www.siemens.com/innovation/en/home/pictures-of-the-future/energy-and-efficiency/smart-grids-and-energy-storage-electrolyzers-energy-storage-for-the-future.html. [Accessed 9 June 2015].

[75] B. Müller, "Really Clean Coal? It’s Possible!," 18 February 2015. [Online]. Available: http://www.siemens.com/innovation/en/home/pictures-of-the-future/energy-and-efficiency/sustainable-power-generation-coal-gasification.html. [Accessed 9 June 2015].

[76] D. Steward, G. Saur, M. Penev and T. Ramsden, "Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Electrical Energy Storage," National Eneregy Renewable Laboratory, 2009.

[77] Research and Development Solutions (RDS), Energy Sector Planning and Analysis (ESPA), "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity," National Energy Technology Laboratory (NETL), 2013.

[78] National Energy Technology Laboratory, "Cost and Performance Baseline for Fossil Energy Plants Volume 2: Coal to Synthetic Natural Gas and Ammonia," 2011.

[79] D. Anderson and M. Leach, "Harvesting and redistributing renewable energy: on the role of gas and electricity grids to overcome intermittency through the generation and storage of hydrogen," *Energy Policy,* vol. 32, no. 4, pp. 1603-1614, 2004.

[80] F. Rigas and S. Sklavounos, "Evaluation of hazards associated with hydrogen storage facilities," *International Journal of Hydrogen Energy,* vol. 30, no. 13, pp. 1501-1510, 2005.

[81] Global Energy Observatory, "Current List of Coal PowerPlants," [Online]. Available: http://globalenergyobservatory.org/list.php?db=PowerPlants&type=Coal. [Accessed 04 08 2017].

[82] International Energy Agency, "Electricity production from coal sources (% of total)," [Online]. Available: http://data.worldbank.org/indicator/EG.ELC.COAL.ZS. [Accessed 04 08 2017].

[83] Central Intelligence Agency, "The World Factbook- Country Comparison- Electricty- Production," [Online]. Available: https://www.cia.gov/library/publications/the-world-factbook/rankorder/2232rank.html. [Accessed 04 08 2017].

[84] European Union, "Countries," [Online]. Available: https://europa.eu/european-union/about-eu/countries_en. [Accessed 04 08 2017].

[85] Euoprean Union, "2030 climate & energy framework," [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2030_en.

[86] European Union, "2050 low-carbon economy," [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2050_en. [Accessed 04 08 2017].

[87] Russian Federation, [Online]. Available: http://climateactiontracker.org/countries/russianfederation.html.

[88] Interfax., "Russia prepared to cut greenhouse gas emissions to 70% by 2030.," 05 04 2015. [Online]. Available: http://rbth.com/news/2015/12/10/russia-prepared-to-cut-greenhouse-gas-emissions-to-70-by-2030_549469. [Accessed 04 08 2017].

[89] E. Gerden, "Plans for wind to replace oil generation in Russia.," 30 11 2016. [Online]. Available: http://www.windpowermonthly.com/article/1417298/plans-wind-replace-oil-generation-russia. [Accessed 04 08 2017].

[90] R. Bandyopadhyay and D. Patiño-Echeverri, "Alternative energy storage for wind power: Coal plants with amine-based CCS," *Energy Procedia,* vol. 63, pp. 7337-7348, 2014.

[91] B. Cheadle, "Can Canada meet its current 2030 climate target? Four experts weigh in," 28 02 2016. [Online]. Available: http://www.ctvnews.ca/politics/can-canada-meet-its-current-2030-climate-target-four-experts-weigh-in-1.2796107. [Accessed 04 08 2017].

[92] Canadian Wind Energy Association, "Wind Force," 24 04 2009. [Online]. Available: http://canwea.ca/pdf/Canadian%20Geographic%20Wind%20postermap.pdf. [Accessed 09 08 2017].

[93] Climate Action Tracker, "United States of America," [Online]. Available: http://climateactiontracker.org/countries/usa.html. [Accessed 04 08 2017].