Complying With The EPA Clean Power Plan – A Techno-Economical Overview

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INTRODUCTION

In order to address the risks of climate change, the US Environmental Protection Agency (EPA) proposed in June 2014 a commonsense plan to cut carbon pollution from power plants – the Clean Power Plan. The plan comprises state-specific rate-based goals for carbon emissions from existing fossil fuel power plants to new build units. However, the plan does not impose any technological obligation, i.e. each federal state is free to choose the technological option that best fits its boundary conditions, infrastructure and available resources. Furthermore, federal states are allowed to work together and develop multi-state plans. Following the timeline of the plan, a total carbon emission reduction by 30% in the power sector must be achieved by 2030 compared to 2005 emissions.

There are numerous technological options to mitigate carbon emissions, such as end-use efficiency improvements and generation efficiency improvements, more use of low-emitting power sources, the use of renewable energy sources such as solar and wind energy, fuel switching and carbon capture and storage (CCS) amongst others. In this paper, the focus lies on technological options to reduce carbon emissions applicable to coal fired power plants and it compares the costs for construction and/or modification and generation costs. Furthermore, technology implementation risks are addressed and possible implementation times are discussed.

The comparison of technology options are existing pulverized coal (PC) power plants with CCS, new built PC power plants with CCS (including IGCC) and direct and indirect co-firing of non-fossil fuels. Power production costs and costs for avoiding CO_2 emissions are calculated. This gives a small overview of what is possible. Based on a local set of boundary conditions one option might favor over the other. Every option comes with a set of challenges, for which ECN provides solution services.

REDUCING CARBON EMISSIONS

There are many options of complying with the Clean Power Plan. In this paper the focus lies on solid fuel conversion technologies, comprising coal, biomass and waste streams. Furthermore, the analysis in this paper is carried out for PC utilities. As a comparison, a natural gas combined cycle is also included.

The second option is using Carbon Capture and Storage (CCS) in combination with either an existing PC boiler, or with a new PC boiler or in combination with an integrated gasification combined cycle (IGCC). These options use a carbon capturing technology and still rely on coal conversion technology to produce power.

A third option is to directly co-fire biomass in an existing PC boiler. The near-term option is to use clean, untreated wood pellets , which would require the installation of an entirely new fuel handling and storage infrastructure, as well as the modification of one or more coal mills to grind and feed these pellets instead of coal. In case torrefied wood pellets are used the infrastructural changes are minor and the mills do not have to be modified; the torrefied wood pellets can be directly blended-in with coal.

A last option which is explored is indirect co-firing via biomass gasification. In this case coal is replaced with a medium calorific gas obtained via gasification of low rank fuels. Demolition wood, agricultural residues or even MSW can replace the coal. In this case the fuel costs will reduce considerably [1].

These seven options are compared to the operation of a standard PC boiler and the following paragraph sheds light on the economics of each option. Next, the associated technological challenges and benefits are discussed and finally some examples of how the knowledge developed at ECN can help utilities in making the right choices in order to comply with the EPA Clean Power Plan.

ECONOMICS

The previously described options were compared with information from existing literature [2]. The efficiency (based on higher heating values) of each option is given below. For CCS applications a reduction of 8%-points is assumed based on the EPA 2013 [2] study. However, for a new super critical boiler the efficiency in the EPA study is rather low, whereas the Trianel Kohlekraftwerk Lünen Power Plant has an efficiency of almost $46\%_{LHV}$ [3]. This number converted to HHV based efficiency was used as a standard efficiency value for a new PC boiler with CCS. The co-firing options have a small decrease in efficiency, with the torrefaction option being the exception. The assumed efficiencies are given in Table 1.

Table 1: Assumed net efficiencies on HHV-basis for different power generating options

Technology	Efficiency
PC Boiler	38.8%
NGCC	53.1%
PC Boiler + CCS	30.8%
New PC Boiler + CCS	35.2%
IGCC + CCS	32.2%
PC Boiler retrofitted 30% biomass	38.4%
PC Boiler retrofitted 30% torrefied biomass	38.8%
PC Boiler retrofitted 30% indirect co-firing	38.2%

For the economic evaluation of the different options the fuel prices in Table 2 were used. The following figures show that the capital costs and the fuel cost are the determining factors in electricity price. Since capital costs cannot be varied, but fuel prices will vary, these are included in the evaluation. An upper and lower limit, based on historical data for coal and natural gas is included. These prices are obtained from IEA [4] and the DOE [5]. All cost figures in this paper are in US$ 2012. For torrefied pellets the price is assumed to be 10% higher compared to standard wood pellets [6], which will have a lower and upper limit of -10% and +25% respectively. The fuel for indirect co-firing can be demolition wood, agricultural waste and refuse derived fuel. Therefore, the price range is in the low case negative and always lower compared to wood pellets.

Table 2: Fuel prices used for calculations, current price, estimated low and high price [$/GJ].

Fuel	Current	Low	High
Coal	2	1.5	3
Gas	4.5	2	12
Wood pellets	9	8.1	11.3
Torrefied wood pellets	9.9	8.9	12.4
Waste	2.6	-2	7.5

Based on these values a comparison has been made for the electricity production costs, expressed in $/kWh, for all three scenarios.

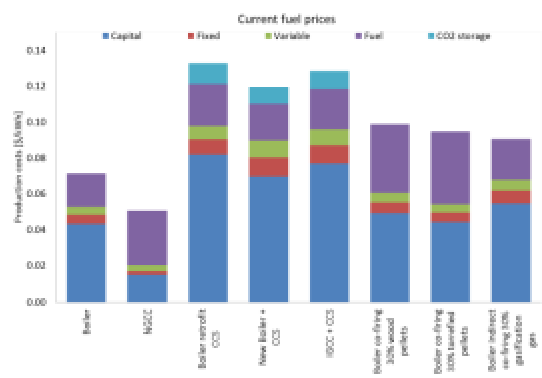

Figure 1: Production costs of electricity at current fuel prices [$/kWh].

At current conditions the production costs of electricity are cheapest for the NGCC route. Natural gas as fuel is about 30% cheaper and co-firing options are about 30% more expensive. CCS options have even higher capital investments and therefore are between 70 and 90% more expensive compared to the base case. The cheapest CCS options is a new PC power plant with CCS, because the efficiency of a new PC boiler is much higher than existing ones. If CO_2 has a price (e.g. Enhanced Oil Recovery (EOR) or greenhouse applications) it can be a good option to use CCS.

The next two cases are based on a low price and a high fuel price scenario. Cases where coal price stays low and gas becomes expensive are not included, but can be deducted from Figure 2 and Figure 3.

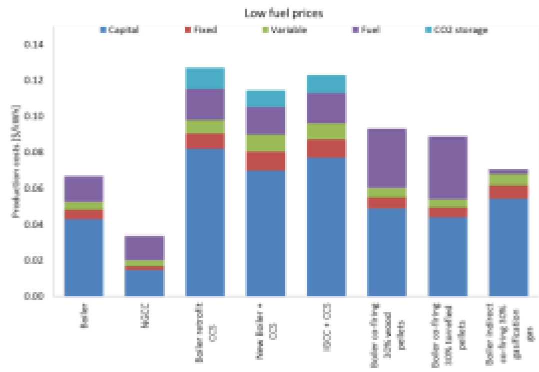

Figure 2: Production costs of electricity assuming low fuel prices [$/kWh].

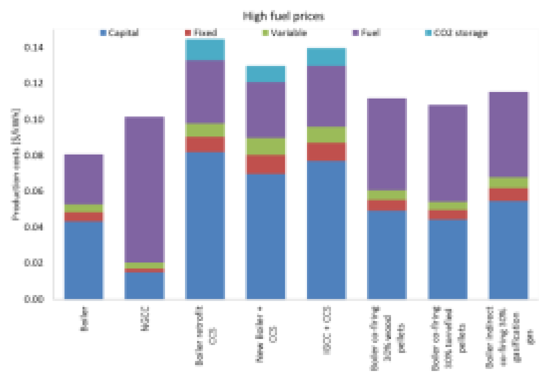

Figure 3: Production costs of electricity assuming high fuel prices [$/kWh].

Currently, gas is the cheapest option to produce electricity and it will also lead to reduced CO2 emissions. However the natural gas price tends to be very volatile. In recent years the gas price was significantly higher, which in a high fuel price scenario would make the production costs even higher than coal based electricity. Largely due to plentiful and affordable natural gas and natural gas liquids from shale formations, US jobs related to plastics manufacturing are expected to grow by 462,000 over the next decade -- more than 20% [7]. This will affect the natural gas price and will give a competition with electricity production.

Co-firing wood pellets or torrefied wood pellets has in all cases a marked influence on the electricity price. But compared to CCS the capital investments are much less, which makes it a good competitor. Also indirect co-firing does not need CCS to achieve the EPA targets and this options allows for more difficult and cheaper fuels. In the low price case, the 30% indirect co-firing is a very lucrative option profit optimization. Even if the coal price would be at the high level, the combination of a negative priced secondary fuel and expensive coal will keep the production price to a minimum.

These options above are compared based on a production price for electricity. However, one can also look at the costs of CO_2 reduction compared with the standard coal-fired boiler. Therefore, the emission reduction and investment costs have been translated into a number which shows how much it costs to reduce carbon emissions. These figures are calculated bases on a kWh production, making it easier to compare. Some remarks need to be made for interpreting the following graph showing these results. Each option has an electricity cost price per kWh and an amount of CO_2 emitted per kWh. These have been compared to the standard pulverized fuel boiler. However, the CCS options reduce ~90% of CO_2, an NGCC ~60% and the co-firing options 30%. The figure contains a value of 16 $/ton CO_2 for transport and CO_2 storage in case of CCS. Depending on the actual storage situation and transport distance, cost might be twice as high [8].

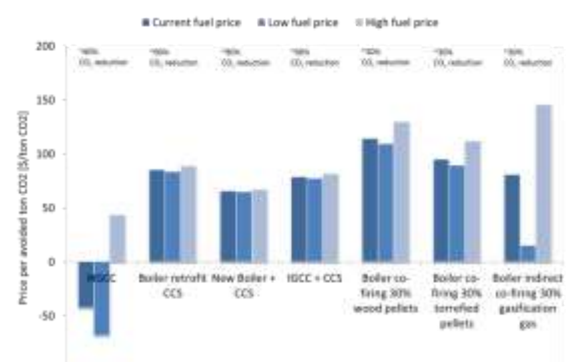

Figure 4: Price per avoided ton of CO_2 for different scenarios [$/ton CO_2].

Figure 4 shows that NGCC as a means to reduce carbon emissions is the cheapest option. The reason for this is the lower capex and the lower fuel costs. It must be noted that this option is very sensitive to the fuel price and the natural gas price is not known for its stability.

The CCS cases have a high production price for electricity, but one installation is capable of reducing up to 90% of the CO2 emissions. This means that two other installations do not need any investment in order to comply with the EPA targets (under current regulations). If the CO2 can be utilized in the vicinity of the plant (for instance for Enhanced Oil Recovery), then additional revenues will be generated making the business case more positive. There are new developments that present a much more favorable case for CCS in terms of efficiency penalty, removal efficiency and capital expenditure [9].

The co-firing options are calculated at 30% CO_2 reduction. Replacing 30% of coal with more expensive fuel will increase the electricity price and therefore the price per ton of avoided CO_2. However, it is a simple solution to achieve a quick reduction and there is no issue with CO_2 that needs to be transported and stored. This solution also maintains the coal boiler as it is. The indirect co-firing option is promising because this allows the use of negatively priced fuels. This reduces the price per ton of avoided CO_2 much more than the other options when a cheap fuel is chosen.

Many possible routes exist to reduce greenhouse gas emissions. Which is the best depends on many factors. Some are listed below.

- How will the natural gas price develop?
- Is there a local market for CO_2?
- What will future emission regulations look like?
- Is there a lot of biomass/waste available at low cost?

TECHNICAL IMPLEMENTATION

All technological options analyzed in this paper have their respective issues. First of all, the technology readiness levels have been described by the EPA [2] and can be summarized as follows.

Table 3: Technological readiness levels

Technology	Status
PC Boiler	mature
NGCC	mature
PC Boiler + CCS	revolutionary
New PC Boiler + CCS	revolutionary
IGCC + CCS	revolutionary
PC Boiler retrofitted 30% biomass	mature
PC Boiler retrofitted 30% torrefied biomass	evolutionary/mature
PC Boiler retrofitted 30% indirect co-firing	evolutionary

It is evident from Table 3 that any option using CCS will have an increased risk because the CCS technology is not yet mature. The net efficiency reduction of 8% combined with the large capex is currently limiting the introduction. However, new improved technology is reaching the market. Also for new power plants the CCS option is perhaps expensive, but because of the increased efficiency this might still be a good option, in particular when there is a price associated with CO_2.

The co-firing applications are marked as mature and evolutionary. Direct co-firing of wood is a widely applied option and it is well understood what the effects are on a boiler. Co-firing torrefied biomass is not yet common practice, but recent large scale demonstrations indicate no major issues [10]. Torrefied pellets were tested in the Amer (25 wt% direct, 5 wt% indirect), Buggenum (70 % co-gasification) and Studstrup-3 (33 wt% co-firing) [11].
Compared to wood pellets, the torrefied wood option has a number of advantages:

1. Lower capex (fuel can be co-milled directly with the coal)
2. Similar price (with sufficient scale the pellet price in $/GJ will be similar to clean wood)
3. Less de-rating, because the fuel behaves similar to coal
4. No storage issues, because torrefied wood pellets are not prone to (biological) degradation

Indirect co-firing is also an evolutionary technology according to the EPA. Since it involves a gasifier which converts waste streams into gas with a connection to the boiler, it is somewhat more challenging than feeding pellets. However, it is being applied at for instance the Amer power plant operated by Essent/RWE in the Netherlands. This installation is used to co-fire demolition wood as well as refuse derived fuel.

TACKLING CHALLENGES

The options to reduce the carbon footprint of the utility park are broad. Wind, solar and tidal are not even included in this study. For the technology options that stay close to the state-of-the-art coal based power production any of the possible options will introduce new risks or issues. These risks can be predicted, prevented or managed and ECN can provide services for achieving these goals.

ECN has been active in solutions providing for biomass co-firing for over 25 years. ECN can provide information on the current practice with respect to transport, on-site handling, storage, milling and pneumatic conveying of biomass during co-firing in coal-fired power stations. A sophisticated lab-scale combustion simulator is available to mimic the effect of co-firing any type of fuel/blend under any type of condition (oxy fuel, enriched air etc.). This installation provides detailed information on achievable co-firing percentages, efficiencies, emissions and slagging and fouling behavior, and minimizes any operational risks to a maximum extent.

The following graph shows characteristics of lean-phase transport of fuel. Coal in this case is the reference and white wood and torrefied eucalyptus are compared. Torrefaction changes the behavior of the material such that it behaves more like coal than biomass.

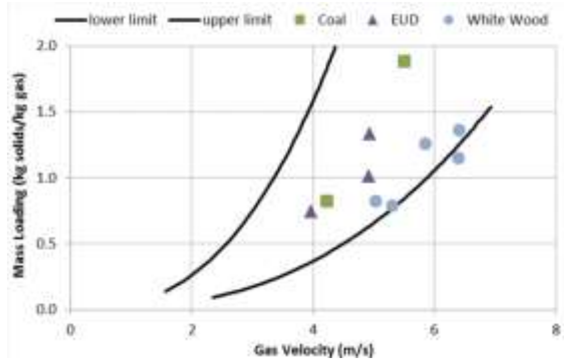

Figure 5: Mass loading of transport gas for lean-phase transport.

Another issue to keep in mind is the explosivity behavior of certain materials. When fuel is milled to fine powder the risk of an explosion increase. Figure 6 shows the Minimum Ignition Energy (MIE) for dust samples.

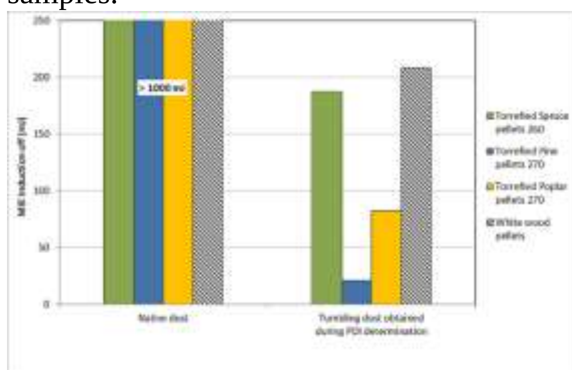

Figure 6: MIE of native dust and tumbling dust of pellet samples (fraction below 500 µm and dried at 75 °C)

The dust obtained from tumbling white wood pellets and the torrefied spruce pellets appears less problematic, since relatively high energy levels are required to cause an ignition. However, interesting enough is the fact that the torrefied pine and poplar actually contained more fines, causing a lower MIE. When these materials are compared on similar particle size distributions (PSD), the MIE for spruce and white wood are the lowest. Furthermore, torrefied material with a PSD between 63 -125 (µm) have an MIE larger than 1000 (mJ) [12].

There is a lab-scale combustion simulator (LCS) available to mimic the effect of co-firing any type of fuel/blend under any type of condition (oxy fuel, enriched air etc.). This installation provides information on co-firing percentages, efficiencies, emissions and slagging and fouling behavior. In the area of gasification ECN has a long standing history of coal, biomass and waste gasification. Also different types of gasifiers have been tested from fixed bed, fluidized bed to entrained flow gasifiers. ECN is providing support to governments on tools they can use to change an energy system from fossil fuel based to a sustainable energy system. ECN is developing carbon capture technology and understands the issues related to traditional CC technology.

Some examples on how ECN is active in the area of service provider to the power sector or in relation to CO_2 reduction are given below.

- Support during direct and indirect co-firing biomass and waste in the Amer-9 power plant in the Netherlands [11].
- Support on the co-gasification of up to 70% in Buggenum, with pellet characterization and consultancy [11].
- Support on the co-firing tests at Studstrup-3, via lab-scale pellets characterization [11].
- Co-author IPCC special report on Carbon Capture and Sequestration
- ECN acted as principal consultant during co-firing trials with torrefied biomass pellets and/or steam exploded pellets in NUON/Vattenfall Buggenum IGCC, RWE/Essent Amer-9 power plant, and DONG Studstrup-3 power plant.
- ECN objectively assesses torrefied biomass pellets and/or steam exploded pellets for end users, amongst others for the CEATI consortium.

CONCLUSIONS

The EPA has announced that it will finalize the proposed Carbon Pollution Standards mid-summer 2015. Assuming that the main target of 30% reduction of carbon dioxide emissions below the 2005 level from the power sector by 2030 will be maintained the power sector will face serious challenges in the near future.

Fortunately, there are many different technological options that can be applied to achieve the targets and the combination of these will make the power sector strong and reliable for the future. Coal as very stable low cost fuel will remain one of the workhorses in the U.S. power sector. Options such as CCS, direct and indirect co-firing will need to play a significant role in this future generation mix. Due to different regulatory reasons in the Netherlands, there is a vast amount of knowledge regarding this options. ECN wants to provide their services to the U.S. power sector to make the transition as smooth as possible.

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