Climate analysis of Subcoal® in coal-fired power plants

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Summary

The Subcoal® concept is a patented technology developed by DSM. Subcoal® pellets are produced from paper-plastic waste streams, such as rejects from the paper industry and residual paper-plastic fractions from sorting plants. The caloric value of Subcoal® is similar to that of coal. The Subcoal® pellets can be pulverized in the same way as coal.

Subcoal® International asked CE Delft to evaluate the climate impact and overall environmental impact of burning Subcoal® in coal-fired power plants. The climate impact of burning Subcoal® in coal-fired plants (Subcoal® route) was compared with that of burning paper-plastic waste (the raw material of Subcoal®) in a waste incineration plant (WIP route).

For burning Subcoal® in a coal-fired power plant, two scenarios were evaluated:

1. **Scenario 1**: one megajoule of Subcoal® substitutes one megajoule of hard coal.
2. **Scenario 2**: one megajoule of Subcoal® substitutes 0.6 megajoules of hard coal and 0.4 megajoules of wood pellets. In this scenario it is assumed that the bio-content of Subcoal® (40% of its energy content) substitutes wood pellets.

In Scenario 1, the Subcoal® route reduces CO_2 emissions by 1,263 kg per tonne of Subcoal® compared with the WIP route. Burning 10% Subcoal® in coal-fired power plants reduces the life cycle climate emissions of a coal-fired power plant by 7%.
In Scenario 2, the Subcoal® route reduces CO_2 emissions by 645 kg per tonne of Subcoal® compared with the WIP route. Burning 10% Subcoal® in coal-fired power plants reduces the life cycle climate emissions of a coal-fired power plant by 3%.

The Subcoal® route was evaluated against a theoretical best-case scenario for the WIP route. In this scenario, the WIP is assumed to generate electricity very efficiently, thus avoiding output from a coal-fired power plant. The difference in CO_2 emissions is 122 kg per tonne of Subcoal® in favour of the Subcoal® route.

The overall environmental impact of the two routes was assessed using the ReCiPe method. The Subcoal® route scores better on 12 of the 18 environmental indicators evaluated. In line with the climate impact analysis, the ReCiPe single-score indicator (weighted score of 18 indicators) shows reduced environmental impacts for the Subcoal® route compared with the WIP route.

The current study is a follow-up to the 2011 study 'Climate analysis Subcoal® - Subcoal® from coarse rejects of the paper industry as fuel for lime kilns'. While that study assessed use of Subcoal® in lime kilns, the present study evaluates burning of Subcoal® in coal-fired power plants. In addition, the present study implemented changes in the Subcoal® production process, including changes in the raw materials used. The figures used for WIP efficiency were also updated.

1 Introduction

The Subcoal® concept is a patented technology developed by DSM.
Subcoal® pellets are produced from paper plastic waste streams, such as rejects from the paper industry and residual paper plastic fractions from sorting plants.
The caloric value of Subcoal® is comparable to that of coal. The Subcoal® pellets can often be ground in the same manner as applied for coal.
Finally the Subcoal® price (without subsidies) is below coal prices which makes it a serious alternative for hard coal.

In 2011, CE Delft conducted a study on the climate impacts of the application of Subcoal® produced from paper/plastic waste paper in Lime kilns.
Since 2011, Subcoal® in Farmsum has also been produced from paper plastic fractions from sorting plants. Furthermore, it has been demonstrated that Subcoal® can be co-fired in coal-fired electricity plants.

Subcoal® International has asked CE Delft to update the climate change analysis of 2011, with application of Subcoal® in coal-fired power plants.
The impact of Subcoal® use on the climate footprint of the electricity production in coal-fired power plants is assessed as well. Finally the overall environmental impact including other environmental indicators will be assessed.

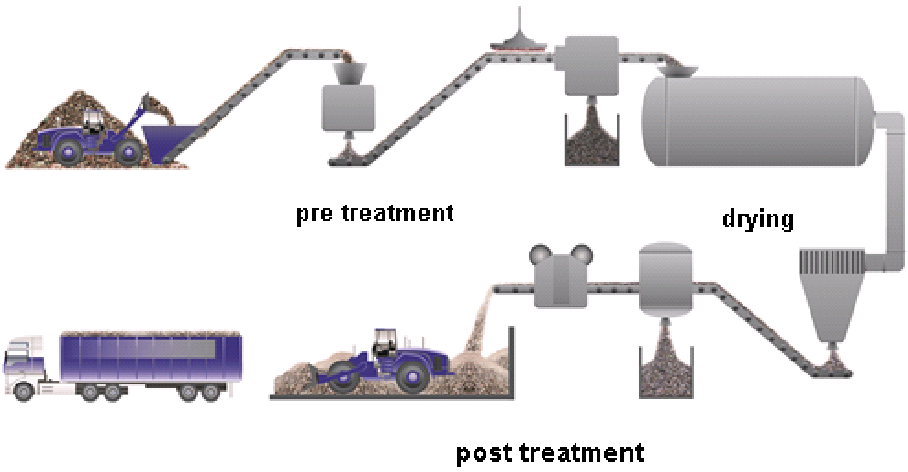
2 Subcoal® process

The Subcoal® process uses plastic paper waste as starting material. Currently, in the factory in Farmsum, the plastic paper waste comes from two different sources: 1) rejects from the paper industry; 2) plastic paper fractions from waste separation installations. In both cases it concerns waste fraction that do not qualify for recycling of either the paper or the plastic.

Figure 1 gives an overview of the production of Subcoal® fuel from paper plastic waste.

After shredding the rejects (35% water content), a sifter separates out heavy part such as stones and metals. By means of a gas fired drum the material is dryed to a water content below 10%. The water vapour is released into the atmosphere via a cyclone and an air scrubber. During the process ferro and non-ferro materials are removed by Eddy current separators and magnets. PCV is being removed by optical separation techniques. Finally the product is pelletized.

Figure 1 Simplified process diagram of the Subcoal® production process



3 System description and scenarios

3.1 System description

Life cycle assessment (LCA) is a method to assess the environmental impacts of products (consumption) and changes in production processes. The LCA methodology has been applied to answer the main question of this report:

“What is the climate effect (in CO_2 equivalents) of co-firing a megajoule of Subcoal® in a coal-fired electricity plant?”

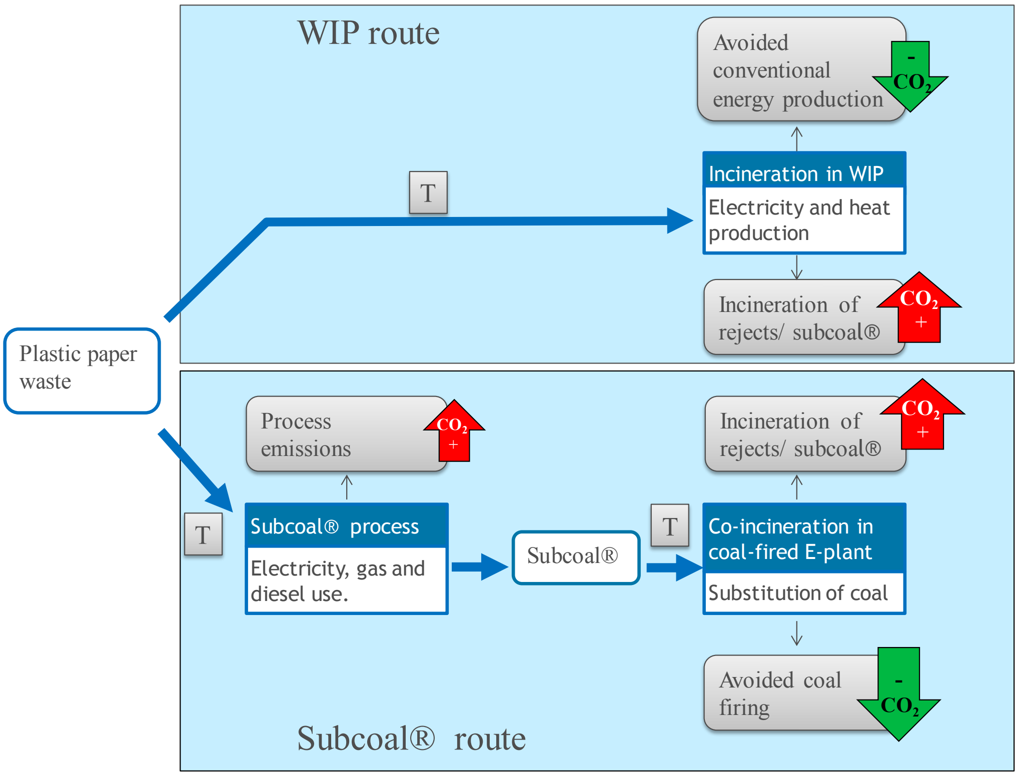
To answer this question it is important to identify and describe all processes that are affected by co-firing Subcoal® in the system to be analysed.

The following assumptions have been made concerning the co-firing of Subcoal® in a coal-fired electricity plant:

- The Subcoal® route is an alternative for incineration of paper plastic waste in waste incineration plants (WIP). In other words: If paper plastic waste is not used for Subcoal® production, it will be incinerated in a WIP. The WIP route is therefore taken as reference situation for the Subcoal® route, against which the Subcoal® route is evaluated.
- A WIP produces electricity and delivers heat (e.g. district heat). The efficiency rate for electricity production and heat delivery is based on the average Dutch WIP park.
- Electricity produced by the WIP avoids conventional electricity production. In the analysis the life cycle climate impact of the average production mix in the Netherlands is assumed. Delivered heat by the WIP avoids life cycle climate emissions of heat production by gas boilers.
- Co-firing one megajoules of Subcoal® in a coal-fired electricity plant avoids the firing of one megajoules of coal. Avoiding the use of coal not only avoids CO_2 emission at the plant but all life cycle emissions related tot the production and transport of coal.

Figure 2 gives a schematic system description, including the elements described above. The upper part of the scheme shows the WIP route. It includes the transport of the paper plastic waste to the WIP, the emissions of incineration and the avoided emissions of conventional electricity and heat production. The lower part of the scheme shows the Subcoal® route. It includes transport of the waste (T), the process emissions of Subcoal® production (gas and electricity use), emissions of the incineration of Subcoal® and the avoided emissions of coal incineration.

Figure 2 Scheme CO_2 emission of WIP and Subcoal® route



For clarity reasons the relatively low CO_2 emissions related to the use of additives (NaOH, $Ca(OH)_2$, NH_4OH, charcoal) for flue gas cleaning in the WIP and the use of additives of flue gas cleaning in power plants (lime, ammonia) are not shown in Figure 2. These CO_2 emission, however, are accounted for in the analysis.

The comparison between the two routes focusses on the Subcoal® content in the plastic paper waste. However, there are other contents in the plastic paper waste fractions (PVC parts, ferro and non-ferro part) that are removed during the Subcoal® process. The extra transport emissions for the removed fractions in the Subcoal® route are accounted for in the analysis. Apart from transport it is assumed that the processing of these waste fractions it is the same in both routes: metal is removed and recycled, PVC is incinerated in an WIP.

3.2 Alternative scenario

In the Dutch ‘Energy Agreement for Sustainable Growth’ a target is set for generating 16% of the Dutch energy generation from renewables. The use of biomass in coal-fired power stations can contribute to this target up to a maximum of 25 PJ (SER, 2013).
About 46% of the carbon content in Subcoal® is biogenic (UCL, 2014).
This corresponds to a contribution of the biogenic content to the heating value of Subcoal® of circa 40%[1]. Subcoal® can be applied in coal-fired power stations to contribute to reach the renewable energy target.

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[1] The bio C content has been valuated assuming originates from paper plastic with a C content of 44.8% and a heating value of 16.8 MJ/kg. The fossil C content has been valuated assuming it originates from plastics with a C content of 75% and a heating value of 35.2 MJ/kg.

It can therefore be argued that not only coal but also wood pellets are substituted when Subcoal® is applied in coal-fired power plants. Therefore, in an alternative scenario the CO_2 score of Subcoal® is evaluated assuming that one megajoules of Subcoal® substitutes 0.6 megajoules of coal and 0.4 megajoules of wood pellets. According to (NL Agency 2011), the life cycle CO_2 emission for firing wood pellets are considered to be 11% of those of coal. These emissions include the CO_2 emissions of transport and pelletization[2].

3.3 Sensitivity analysis WIP route

The WIP route described in Section 3.1 assumes an average Dutch WIP, with average efficiency. The electricity produced by the WIP route is assumed to avoid average conventional electricity production in the Netherlands.

In specific situations the WIP efficiency might, however, be higher or lower. The effect of different WIP efficiencies will be evaluated in a sensitivity analysis.
Furthermore a best case scenario for the WIP route is evaluated assuming that electricity from coal-fired power plants is avoided by generating electricity in in a WIP. In reality this scenario is not likely as both WIPs and coal-fired power plant are considered as 'Must-run' power supply units. However, as electricity from coal-fired power stations is most climate intensive, this scenario gives the upper limit climate performance for the WIP route. It will be evaluated how the best case WIP scenario scores relatively to the Subcoal® route.
For this analysis it is assumed that coal-fired Power plants use 12.5% biomass (wood pellets) and 87.5 % hard coal as fuel (based on CE Delft, 2014) .

2 Life cycle climate emissions of burning wood pellets are probably underestimated in the method, as the method does not take into account lower carbon uptake and storage in the soil of forests.

4 Climate impact of Subcoal®

4.1 Result of scenarios

Table 1 and Table 2 summarize the climate impact contributions of the WIP and Subcoal® route, as described in Section 3.1 and 3.2. Details on the underlying calculations can be found in Annex A and B.
In the WIP route the net CO_2 emissions amount 313 kg per tonne of Subcoal®. The most important contributions come from the incineration emissions of Subcoal® (970 kg/tonne) and the avoided emissions of conventional electricity (-425 kg/tonne) and heat (-248 kg/tonne) production.
In the Subcoal® route the CO_2 contributions in both scenarios add up to negative values. This means that applying Subcoal® in coal-fired power plants avoids emissions (as compared to coal firing). In Scenario 1 (100% coal substitution) 951 kg CO_2 per tonne of Subcoal® is avoided. In Scenario 2 (60% coal substation, 40% wood pellets) 333 kg/CO_2 per tonne of Subcoal is avoided. The most important contributions come (again) from the incineration emissions of Subcoal® (970 kg/tonne) and the avoided emissions of using coal.
The difference between Scenario 1 and 2 is solely due to the difference in avoided hard coal/wood pellet use between the two scenarios.

Table 1 Climate impact contributions in WIP route

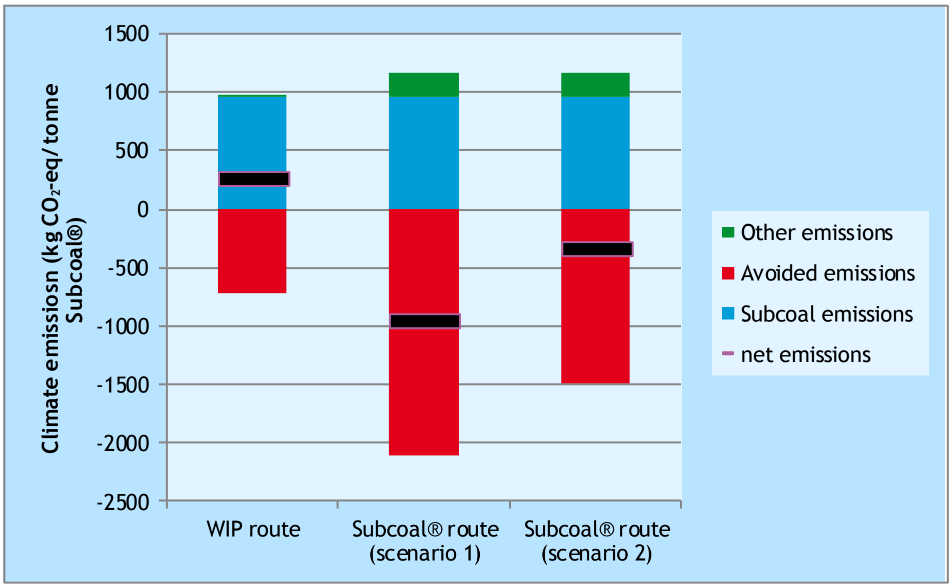
Incineration in AEC	**(Kg CO_2 eq./tonne Subcoal®)**
Incineration of Subcoal®	970
Avoided electricity	-425
Avoided Heat	-248
Transport	3
NaOH (50%) use	5
Lime use	6
Ammonia use	1
Processing of slag and fly ashes	1
Total WIP route	**313**

Table 2 Climate impact contributions in Subcoal® route

Co-incineration in coal-fired electricity plant	**Scenario 1: Coal/substitution (kg CO_2/tonne Subcoal®)**	**Scenario 2: Coal/ wood substation (kg CO_2/tonne Subcoal®)**
Incineration of Subcoal®	970	970
Avoided coal (and wood pellet) firing	-2,111	-1,493
Electricity use Subcoal® process (kWH/tonne)	60	60
Gas use Subcoal® process (MJ/tonne)	84	84
Lime use (net)	-5	-5
Transport	51	51
Total Subcoal® Route	**-951**	**-333**

Comparing the WIP and Subcoal® route it can be concluded that applying rejects in the Subcoal® route instead of the WIP route **CO_2 emission are avoided by 1,263 kg per tonne of Subcoal® (Scenario 1) or 645 kg per tonne of Subcoal® (Scenario 2).**
The differences between the routes are illustrated in Figure 3. The figure illustrates that the difference between the two routes are mainly determined by the avoided emissions. In the comparison, the climate emissions of Subcoal® incineration play no role, as they are the same in both routes.

Figure 3 Climate impacts contributions of WIP route and Subcoal® route (2 scenarios)



4.2 Sensitivity analysis of results

As shown in Section 4.2, the climate impact of the WIP route is mainly determined by the avoided emissions of electricity and heat production by the WIP. These avoided emissions strongly depend on the efficiency of the WIP and the assumptions made regarding the avoided electricity mix. To assess the influence of these parameters on the outcome of the comparison with the Subcoal® route, four alternatives have been evaluated for the WIP route next to the average WIP route.
For the avoided electricity mix, next to the average Dutch production mix, electricity from coal-fired power plants is considered in a theoretical best case scenario for the WIP route. The influence of the WIP efficiency has been varied with scenarios assuming a low and high overall (electricity ad heat) efficiency and a high electric efficiency. The WIP efficiencies reflect the average of the top 3 (best or worst scoring) WIPs in the Netherlands (see CE Delft, 2015a).
The different scenarios for the sensitivity analysis are summarized in Table 3.

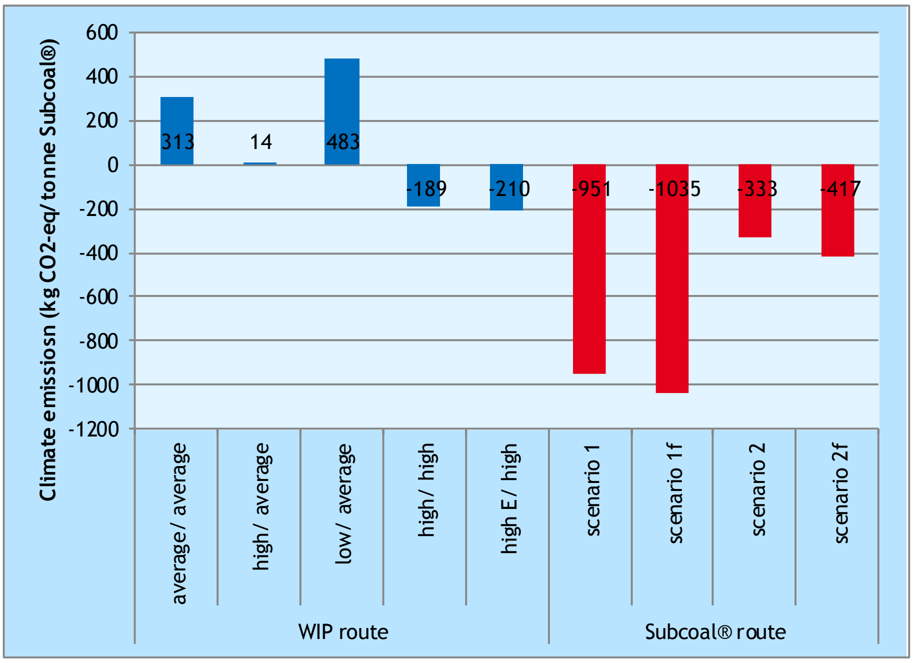
Table 3 **Sensitivity analysis scenarios for WIP route**

Referenced name	WIP efficiency	Avoided electricity
Average/ average	Average (16% electric, 19% heat)	Average production mix NL (466 g/kWh)
High/ average	High (11% electric, 52% heat)	Average production mix NL (466 g/kWh)
Low/average	Low (16% electric, 2% heat)	Average production mix NL (466 g/kWh)
High/coal	High (11% electric, 52% heat)	Electricity from coal-fired power plant (790 g/kWh)
High E/coal	High (26% electric, 2% heat)	Electricity from coal-fired power plant (790 g/kWh)

In the future, Subcoal® International intents to have Subcoal® plants that produce Subcoal® from relatively dry raw material. It is expected that the same quality of product can be produced without the drying process. In this case the gas use in the process would be omitted. The climate effect hereof is evaluated in Scenario 1f and Scenario 2f.

The climate impact results for the WIP routes with alternative assumptions are shown in Figure 4 (blue) next to the results for the Subcoal® route.
The lowest climate impact (-210 kg/tonne Subcoal®) for the WIP route is obtained assuming a high electric WIP efficiency and assuming the electricity produced by the WIP avoids electricity produced by a coal-fired power plant. The climate impact of the Subcoal® route in both scenarios, however, is still lower than the climate impact of this WIP scenario. The main reason is the higher electric efficiency of the coal-fired power plant and therefore a higher amount of substituted coal.
In the different scenarios **the minimum CO_2 reduction for the Subcoal® route amounts 122 kg CO_2 eq./tonne** (difference between high E/high and Scenario 2). **The highest CO_2 reduction amounts 1.5 tonne CO_2 eq.** (difference between low/average and Scenario 1f).

Figure 4 **Sensitivity analysis results for climate impacts WIP route compared to Subcoal® route**



4.3 Climate impact of Subcoal® on electricity footprint of coal-fired power plants

Applying Subcoal® in coal-fired power plants will reduce CO_2 emissions of the electricity produced. For the two main Subcoal® scenarios the climate impact on the CO_2 footprint of electricity from coal-fired power plants is assessed assuming a share of 10% Subcoal® in the fuel input. For coal-fired power plants the fuel input amounts 8.4 MJ/kWh (CE Delft, 2013). A 10% substitution of the fuel input thereby corresponds to 41 grams of Subcoal/kWh.
The Corresponding CO_2 reduction amounts 52 g/kWh (Scenario 1) or 26 g/kWh (Scenario 2). Depending on the assumed fuel mix of coal-fired power plants, the life cycle CO_2 reduction of applying Subcoal® is 6-7% in Scenario 1 and 3% in Scenario 2.

	Scenario 1a	Scenario 1b	Scenario 2
CO_2 emissions electricity from a coal-fired power plant (g/kWh)*	889	790	790
MJ/kWh input	8	8	8
10% Subcoal (MJ/kWh)	0.84	0.84	0.84
10% Subcoal (kg/kWh))	0.041	0.041	0.041
CO_2 reduction average (g/kg)	-1,263	-1,263	-645
CO_2 reduction average (g/kWh)	-52	-52	-26
Relative Climate impact reduction	-6%	-7%	-3%

* In Scenario 1a CO_2 emissions for electricity are based on 100% coal firing. In Scenario 1b and 2 an average of 12.5% wood pellets-co firing is assumed.

5 Other environmental indicators

5.1 Introduction

Climate change is only one of the environmental indicators that can be studied in LCA analysis. In the ReCiPe method for LCA analysis (ReCiPe, 2015) 17 other indicators are distinguished:

1. Ozone depletion
2. Terrestrial acidification
3. Freshwater eutrophication
4. Marine eutrophication
5. Human toxicity
6. Photochemical oxidant formation
7. Particulate matter formation
8. Terrestrial ecotoxicity
9. Freshwater ecotoxicity
10. Marine ecotoxicity
11. Ionising radiation
12. Agricultural land occupation
13. Urban land occupation
14. Natural land transformation
15. Water depletion
16. Metal depletion
17. Fossil depletion

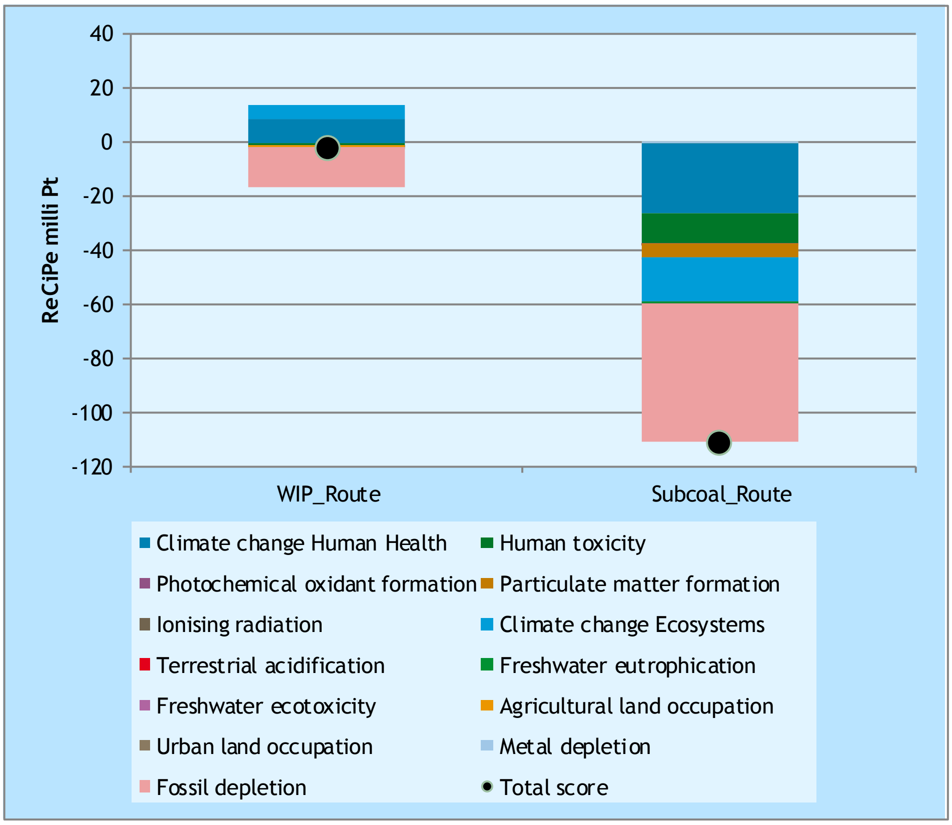
Evaluation of these indicators require an in-depth analysis and measurements of all emissions to water air and soil in the total life cycle chain of the processes studied. A complete evaluation of all emissions of Subcoal® and coal in power plants and WIPs is beyond the scope of this research.
However, to get an indication of the above mentioned environmental impacts, emissions were modelled using emissions models of WIPs and coal-fired power plants described in (AOO, 2002) and elemental analysis reports of Subcoal® and coal (see Annex A-C)). Emissions of other life cycle processes, such as coal supply and electricity production have been modelled using the life cycle inventory database (Ecoinvent 3.0.1). This evaluation has been modelled for the WIP route (average assumptions) and Subcoal route Scenario 1.

The ReCiPe method also comprises a method in which the environmental indicators are weighted to a single environmental score which is expressed in ReCiPe-points (ReCiPe, 2015). The results of the ReCiPe analysis will be presented in the next section. Details on the modelling can be found in Annex C.

5.2 Environmental impacts of Subcoal® and WIP route

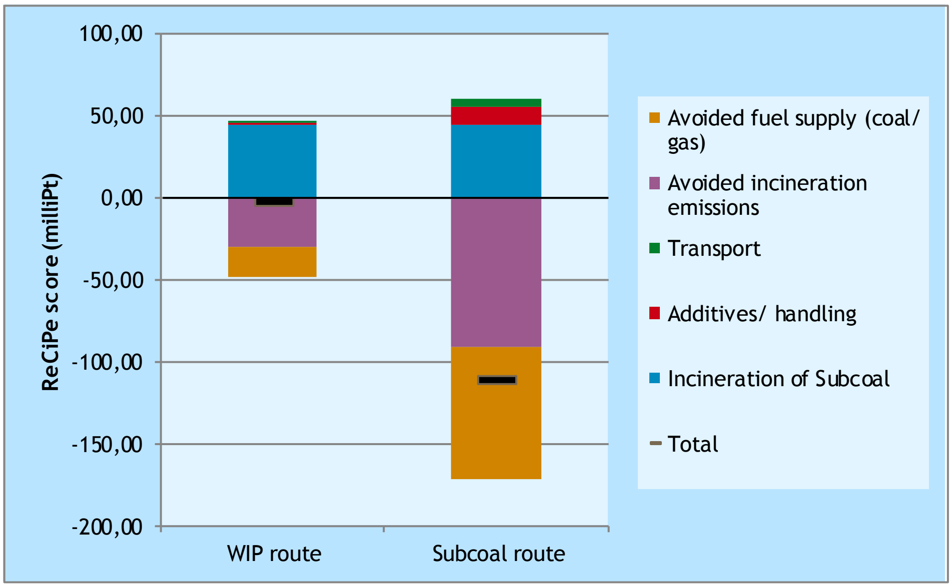
The results for the ReCiPe analysis are shown in Figure 5. The overall ReCiPe results (single score) are relatively comparable to the climate impact results. The Subcoal® route has a net negative environmental impact of -111 ReCiPe milli-points, whereas the WIP route has an impact of -2 ReCiPe milli-points. For the individual indicators contributing to the overall score, the relative scores vary. From the 18 environmental indicators, six have a better score in the WIP route and 12 in the Subcoal® route (see Annex D). The indicators with high contributions to the single score, however, all score better in the Subcoal® route. As can be seen from the figure, climate change and fossil depletion have a strong contribution to the overall ReCiPe score.
Other important indicator that add to the overall score are human toxicity and particulate matter formation.
In both scenarios fossil depletion scores negative as the production of energy from Subcoal® prevents the use of fossil fuels; in the Subcoal® route more effectively. The score for human toxicity is almost completely related to the disposal of spoil from coal mining. In both routes, but to higher extent in the Subcoal® route, the avoided coal usage results in negative human toxicity impact values. Particulate matter formation is mainly related to incineration and supply of coal, Subcoal®, and gas, sea transport of coal and road transport in general.

Figure 5 **Contribution of environmental indicators to ReCiPe score of WIP and Subcoal® route**



To give more insight in the contribution of the different life cycle stages to the total environmental impact, Figure 6 gives the contribution of different life cycle stages to the overall ReCiPe score. Besides the environmental impacts at the incineration plants, the environmental impact in the supply chain of fuels play an important role.
Especially in the Subcoal® route, the avoided hard coal supply has a high contribution tot the total impact. The impacts of the supply chain mainly have their impact abroad. The incineration impacts are local emissions.

Figure 6 **Contributions of life cycle stages to ReCiPe results of WIP and Subcoal route**



The ReCiPe method has only been applied to evaluate Scenario 1 for the Subcoal® route. From Figure 6 it can, however, be concluded that also in Scenario 2 the Subcoal® route will score better. In Scenario 2 the avoided emission will be lower as one megajoules of Subcoal® substitutes only 0.6 megajoules of coal. But even when avoided impacts are reduced by 40% (assuming no avoided impact for wood pellets) the total ReCiPe score of the Subcoal® route will be lower than the ReCiPe score of the WP route.

6 Conclusion

The Climate impact of applying Subcoal® in coal-fired power plants has been evaluated against incineration of paper plastic waste (the raw material of Subcoal®) in a waste incineration plant (WIP). With regard to the incineration of hard coal in a coal-fired power plant two scenarios have been evaluated:

1. **Scenario 1**: one megajoules Subcoal® in a coal-fired power plant substitutes one megajoules of hard coal.
2. **Scenario 2**: one megajoules Subcoal® in a coal-fired power plant substitutes 0.6 megajoules of hard coal and 0.4 megajoules of wood pellets. In this scenario it is assumed that the bio-content of Subcoal® (40% of energy content) substitutes wood pellets.

In Scenario 1, the Subcoal® route reduces 1,263 kg/CO_2 per tonne of Subcoal® as compared to the WIP route. Applying 10% Subcoal® in coal-fired power plants reduce life cycle climate emissions of a coal-fired power plant by 7%. In Scenario 2, the Subcoal® route reduces 645 kg/CO_2 per tonne of Subcoal® as compared to the WIP route. Applying 10% Subcoal® in coal-fired power plants reduce life cycle climate emissions of a coal-fired power plant by 3%.

In a sensitivity analysis, the Subcoal® route has been evaluated against a theoretical best case scenario for the WIP route. In this scenario the WIP is assumed to have a high efficiency in electricity production to avoid electricity production in coal-fired power plant. The difference in CO_2 emissions is 122 kg per tonne of Subcoal® in favour of the Subcoal® route.

The overall environmental impact of the two routes has been evaluated by the ReCiPe method. From the 18 environmental indicators that have been evaluated, 12 indicators score better in the Subcoal® route. In line with the Climate impact analysis, the ReCiPe indicator single score shows reduced environmental impacts for the Subcoal® route as compared to the WIP route.

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Annex A Input parameters WIP route

The climate impact of the WIP route is calculated using the input variables in Table 4-Table 6. The resulting inputs, applied CO_2 emission factors and resulting CO_2 emissions are summarized in Table 7.

Table 4 **Subcoal properties**

Parameter	Value
Carbon content Subcoal (dry)	53%
Bio C in total C (%)	46%
S (dry)	0.17%
Cl (dry)	1.0%
F (ppm) (dry)*	50
Hg (ppm) (dry)	0.19
Water content	7.5%
Lower heating value (MJ/kg) (as received)	20.5

Source: (UCL, 2014).

* Estimated on base of (UCL, 2014).

Table 5 **WIP efficiencies**

Efficiency	Electric (net) efficiency	Delivered Heat
Average	16%	19%
High	11%	52%
Low	16%	6%
High, electric	26%	2%

Source: (CE Delft 2015a, based on RVO data).

Table 6 **Input parameters for WIP**

Parameter	Value
Transport from waste sorting plant to WIP (tkm/ton)	20[a]
NaOH (50%, kg/tonne)	5.08
Lime (kg/tonne Subcoal®)	7.35
Amonia (kg/tonne Subcoal®)	0.317
Processing of slag ans fly ashes (kg/tonne Subcoal®)	144.31

Source: (AOO, 2002), the amount of additives are determined by formulas in (AOO, 2002) using input value from Table 4.

[a] The distance for the WIP route is a low estimate as it is based on the average distance between from the location where waste is produced to the nearest WIP. In reality waste is often transported to WIPs further away.

Table 7 Input values, CO_2 factor and contributions to WIP route

Inputs for WIP route	Input	Unit/tonne Subcoal	CO_2 factor (kg CO_2/unit)	Source CO_2 factor	CO_2 (kg/CO_2/ tonne)
Incineration of Subcoal®	1.0	Tonne	970	Table 4	970
Avoided electricity	3.3	GJe	129	CE Delft 2014	-425
Avoided Heat	3.9	GJ	64	CE Delft 2014	-248
Transport	20	Tonne-km	0.15	Ecoinvent 3.01	3
NaOH (50%)	5.08	Kg	1.0	Ecoinvent 3.01	5
Lime use	7.35	Kg	0.75	Ecoinvent 3.01	6
Ammonia	0.32	Kg	2.10	Ecoinvent 3.01	1
Processing of slag and fly ashes	144.31	Kg	0.0088	Ecoinvent 3.01	1
Total WIP route					**313**

Annex B Input parameters Subcoal® route

The climate impact of the Subcoal® route is calculated using the inputs variables in Table 4, Table 8 and Table 9. The resulting inputs, applied CO_2 emission factors and resulting CO_2 emissions summarized in Table 10.

Table 8 Hard coal properties

Parameter	Value
Carbon content Coal (dry)	62%
S (dry)	0.70%
Cl (dry)	0.044%
F (ppm) (dry)	104
Hg (ppm) (dry)	0.0091
Water content	11%
Lower heating value (MJ/kg) (as received)	24.4

Table 9 Input parameters coal-fired power plant

Parameter	Value
Electricity consumption Subcoal® proces (kWh/tonne Subcoal®)	123
Natural gas consumption Subcoal® proces (MJ/tonne Subcoal®)	1,464
Transport (tonne-km/tonne Subcoal®)*	508
Net lime use (Subcoal hard coal) (kg/tonne Subcoal®)	-6.75
Avoided hardcoal (tonne hard coal/tonne Subcoal®)	0.84

* Transport in based on 200 tonne-km pre and post transport of Subcoal®. Extra transport of the removed parts in the Subcoal® process (35% of rejects) as compared to the WIP route (20 tkm) is also accounted for (2*200/65%-20=508).

Table 10 Input values, CO_2 factor and contributions to Subcoal® route

Inputs Subcoal® route	Input	Unit/ tonne Subcoal	CO_2 factor (kg CO_2/unit)	Source CO_2 factor	CO_2 (kg/ CO_2/ tonne)
Incineration of Subcoal®	1.0	Tonne	970	Table 4	970
Avoided coal firing	0.84	Tonne	2,512	Ecoinvent 3.01	-2,111
Electricity use Subcoal® process (kWH/tonne)	123	kWh	0.489	CE Delft 2014	60
Gas use Subcoal® process (MJ/tonne)	1,464	MJ	0.057	Ecoinvent 3.01	84
Lime use (net)	6.75	kg	0.704	Ecoinvent 3.01	-5
Transport	508	kg	0.100	Ecoinvent 3.01	51
Total Subcoal® route					**-951**

Annex C Input parameters environmental score

The environmental score according to ReCiPe has been modelled in the LCA tool SimaPro. Emissions in WIPs and coal-fired power plants to air, soil and water have been modelled according to the models described in (AOO, 2002). Emissions according to these models are related to the composition of the input. Besides the input values for coal and Subcoal® in Annex A and B the input values in Table 11 have been applied. Other processes have been modelled using (Ecoinvent 3.01) in SimaPro, based on the input parameters described in Annex A and B.

Table 11 Input values for models

Content in ppm (dry)	Hard coal (AOO, 2002)	Subcoal® (UCL, 2014)
– As	3.55	2.4
– Cd	0.093	1.3
– Cl	444	10,000
– Co	4.88	3.5
– Cr	14.5	34
– Cu	13.3	120
– F	104	50
– Hg	0.091	0.19
– Mn	36.4	71
– Ni	8.9	8.6
– Pb	6.39	44
– V	24.8	8.6

The used models for the WIP and the coal-fired power plants are rather static models. Emissions in the model scale linearly with material properties.
In reality emissions might not always be linearly related to heating value or the metal contents of the fuel. For example, Hg emissions to air might be reduced when the Cl content is higher. Flue gas cleaning of Hg is more efficient for Hg as $HgCl_2$ (CE Delft, 2002). Also NO_x emissions not only depend on the heating value (as modelled), but also on the volatility of the fuel. NO_x emissions of Subcoal might, due volatile components in plastic, be relatively low as compared to coal (CE Delft, 2002).
Nonetheless, the modelling is expected to give a good indication on the relative scores of the two evaluated routes.

Annex D ReCiPe midpoint scores

Table 12 Midpoint scores WIP and Subcoal® route

Effect category	Unit		WIP route	Subcoal® route
Climate change	Kg CO_2 eq.	Climate change (kg CO_2 eq.)	3E-01	-1E+00
Ozone depletion	Kg CFC-11 eq.	Ozone depletion (kg CFC-11 eq.)	-2E-08	-1E-08
Terrestrial acidification	Kg SO_2 eq.	Terrestrial acidification (kg SO_2 eq.)	-2E-04	-4E-03
Freshwater eutrophication	Kg P eq.	Freshwater eutrophication (kg P eq.)	-1E-04	-1E-03
Marine eutrophication	Kg N eq.	Marine eutrophication (kg N eq.)	-3E-05	-3E-04
Human toxicity	Kg 1,4-DB eq.	Human toxicity (kg 1,4-DB eq.)	-9E-02	-8E-01
Photochemical oxidant formation	Kg NMVOC	Photochemical oxidant formation (kg NMVOC)	2E-05	-2E-03
Particulate matter formation	Kg PM_{10} eq.	Particulate matter formation (kg PM_{10} eq.)	-2E-05	-1E-03
Terrestrial ecotoxicity	Kg 1,4-DB eq.	Terrestrial ecotoxicity (kg 1,4-DB eq.)	1E-06	8E-06
Freshwater ecotoxicity	Kg 1,4-DB eq.	Freshwater ecotoxicity (kg 1,4-DB eq.)	-2E-03	-2E-02
Marine ecotoxicity	Kg 1,4-DB eq.	Marine ecotoxicity (kg 1,4-DB eq.)	-2E-03	-2E-02
Ionising radiation	kBq U235 eq.	Ionising radiation (kBq U235 eq.)	-7E-02	-1E-02
Agricultural land occupation	m^2a	Agricultural land occupation (m^2a)	-3E-03	2E-04
Urban land occupation	m^2a	Urban land occupation (m^2a)	-1E-03	-1E-02
Natural land transformation	m^2	Natural land transformation (m^2)	-6E-06	-4E-05
Water depletion	m^3	Water depletion (m^3)	-2E-03	-1E-03
Metal depletion	Kg Fe eq.	Metal depletion (kg Fe eq.)	-1E-03	1E-04
Fossil depletion	Kg oil eq.	Fossil depletion (kg oil eq.)	-1E-01	-5E-01