AALBORG UNIVERSITY

DEPARTMENT OF DEVELOPMENT AND PLANNING

LIFE CYCLE ASSESSMENT OF WHEAT STRAW AS A FUEL INPUT FOR DISTRICT HEAT PRODUCTION

Photo: by R.Parajuli

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Master thesis (30 ECTS)

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ABSTRACT

Introduction: Denmark has a long term sustainable energy management goal and aims to maximise the share of renewable energy sources in its total energy mix, demanding massive penetration of biomass sources. Crop residue such as straw is one of the alternative sources of renewable energy in different forms of energy conversion process including heat/power production of the country. Despite this, removal of such residues are generally found debatable such as, its negative effect on soil fertility. The main aim of this study is to assess the environmental performances of Wheat straw as a fuel alternative for district heat production in a Combined Heat and Power (CHP) plant.

Scope, Materials and methods: This study discusses about environmental impacts of straw fired district heat production in a CHP plant, and compares with the alternative fuels natural gas (NG) and imported Wood pellets. *The goal and scope of the study is to assess the life cycle impact based on the impact categories: Non-Renewable Energy (NRE) use, Global Warming Potential (GWP)-100 years, Acidification Potential (AP), and aquatic and terrestrial Eutrophication Potential (EP).* The functional unit for the LCA is 1 MJ of heat output. The system boundary for the straw fired district heat production includes the life cycle processes (1) straw removal (2) collection and pre-processing (3) combustion (4) management of fly ash and bottom ash. The co-produced electricity from the CHP is assumed to displace the environmental impacts of a substitutable marginal electricity production. Three substitutable marginal electricity scenarios are developed, which are NG and coal fired power plant, and Wind power (me1, me2, and me3 respectively). Likewise, nutrient values estimated from the bottom ash are also regarded as a co-product of the system and is assumed to displace the impacts associated with the production of the equivalent amount of chemical fertilizers.

A simple economic evaluation of fuel alternatives is also carried out on the basis of economic indicators: Net Present Value (NPV), Equivalent Annualised Cost (EAC) and Levelised Production Cost (LPC). An ideal CHP plant with thermal capacity of 10 MW is assumed for the economic evaluation.

The study also compares the life cycle impact of district heat production in a CHP with a boiler producing heat only, and is presented in the Article-I (appendix 18). Fuels considered for this comparison is straw and NG.

Results and Discussions:

Straw fired Cogeneration unit: For every 1 MJ of heat production, straw fired in a CHP and substituting the coal fired power plant as the marginal electricity production, would lead to a GWP at -86.54 g CO_2-eq, and NRE use at -1.23 MJ-primary. With the same marginal electricity substitution, AP is 0.008 m^2 UES/MJ heat Likewise, aquatic and terrestrial EP are 0.125 g NO_3-eq /MJ heat and 0.006 m^2 UES/MJ heat respectively. The co-produced electricity and nutrients values in the bottom ash have significant role in lowering the environmental impacts, most importantly the former facilitates significantly to ensure an environmentally efficient mode of energy conversion process. If NG fired power plant and Wind power are assumed as the marginal production, then the net GWP are

estimated at -42 g CO_2-eq/MJ heat and 25 g CO_2-eq/MJ heat respectively, and the net NRE use is at -0.8 MJ-primary/MJ heat and 0.07 MJ-primary/MJ heat respectively.

Wood Pellets fired Cogeneration unit: Wood pellets as a fuel input with the marginal electricity scenarios me1, me2 and me3 would lead to a GWP of 91, 47, 158 g CO_2-eq/MJ heat respectively. AP is estimated at 0.0027 m^2UES/MJ heat, if coal is assumed as the substitutable marginal electricity production. This reveals that the AP in the wood pellets is relatively lower than the straw fired plant. Similarly, Wood pellets leads to aquatic and terrestrial EP at 0.0064 g NO_3-eq/MJ heat and 0.004 m^2UES/MJ heat respectively, and NRE use at -0.96 MJ-primary/MJ heat, with coal as the marginal electricity.

***NG fired Cogeneration Unit*:** NG fired in a CHP plant leads to GWP of -1.41 g CO_2-eq, AP -0.002 m^2UES, aquatic and terrestrial EP at -0.0014 g NO_3-eq and 0.0002 m^2UES respectively, and NRE use at 2.11 MJ-primary for every 1 MJ of heat production, assuming coal as the substitutable marginal electricity production. This reveals that NG would lead to higher GWP and NRE use, but lower AP and EP (both terrestrial and aquatic).

Economic Evaluation: The LPC of district heat in a straw fired CHP plant is estimated at 0.008 €/MJ, if coal fired power production is assumed to be displaced by the co-produced electricity. The estimated LPC is 69% and 41% lower in straw fired cogeneration unit compared to the NG and imported Wood pellets respectively, assuming the similar displacement of the marginal electricity as stated above.

Results of Article-I: The article assesses about the environmental performances of district heat production in a straw fired CHP and compares with the boiler producing heat only. The assessment reveals that for every 1 MJ of district heat production, straw fired in a boiler leads to GWP of 23.73 g CO_2-eq, AP 0.008 m^2 UES, aquatic and terrestrial EP at 0.09 g NO_3-eq and 0.01 m^2 UES respectively, and NRE use at 0.134 MJ-primary. CHP performs better than the boiler for the same heat output. This further reveals that the co-produced electricity has a significant role in lowering the environmental impacts.

Conclusions: Straw performs better compared to Wood pellets and NG in relation to district heat production from the stand point of GWP and NRE use, but leads to higher AP and EP. From the economic perspectives, straw fired in a CHP has better economic returns compared to other fuels considered in this study.

Finally, since biomass acts as storable renewable energy source and is important in conjunction with the fluctuating renewable energy technologies such as Wind power, straw fired CHP producing both heat and power could be regarded as a viable alternative in the Danish future energy mix and also important in fulfilling its decentralized energy/heat demand.

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Ranjan Parajuli

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LIST OF ABBREVIATIONS

AP	Acidification Potential
C	Carbon
CHP	Combined Heat and Power
CH_4	Methane
CO_2	Carbon dioxide
CoWS	Combustion of Wheat Straw scenario
CoNG	Combustion of Natural Gas scenario
CoWP	Combustion of Wood pellets scenario
DKK	Danish Kroner
DM	Dry matter
EP	Eutrophication Potential
g	Gram
GHG	Greenhouse gas
GJ	Giga joule
GWP	Global Warming Potential
ha	Hectare
HCl	Hydro chloric acid
IPCC	Inter Governmental Panel on Climate Change
K	Potassium
Kg	Kilogram
kWh	Kilowatt hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
me	Marginal electricity
M€	Million Euro
Mha	Million hectare
Mkm^2	Million square kilometre

Mt	million ton
MJ	Mega joule
MWh	Mega Watt hour
m^2	Square metre
N	Nitrogen
NG	Natural gas
NO_3	Ammonia
NO_x	Oxides of Nitrogen
N_2O	Nitrous oxide
PJ	Peta joule
P	Phosphorous
SOC	Soil Organic Carbon
Sox	oxides of sulfur
t	Ton
t-km	Ton kilometre
t CO_2-eq	Ton of carbon dioxide equivalent
UES	unprotected Eco-system.
€	Euro (1 € = 7.46 DKK)

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CHAPTER-1: INTRODUCTION

1.1. Background

The approved climate change package of the European Union has highlighted to increase the share of renewable energy from 6.7% in 2005 to 20% by 2020, which is in addition to a 20 % increase in energy efficiency (EEA 2008). The increased share of renewable energy further demands the higher share of biomass contributing to about two thirds of this target (COM 2006). Along with the environmental challenges with the maximised use of bioenergy, the economic efficiency of bioenergy has also been regarded as an important factor in the future market penetration (Celia and Johannes 2010). Agricultural products and waste materials such as straw or other stalk, energy crops (Miscanthus), leaves etc., are becoming increasingly popular, since they are regarded as abundantly available and internationally likely to drive up prices, calling the most efficient and appropriate use of the biomass resources (Lewandowski et al. 2000; McKendry 2002; Powlson et al. 2005; Celia and Johannes 2010). In spite of the growing attention and wider application of biomass in sectors including transport, power and heat (Kgathi et al. 2012), a number of critics on its use exist, primarily from the perspectives of life cycle impacts (EEA 2006; Dickie 2007; Sheehan 2009; Cherubini 2010; Malça and Freire 2011). Among different critics on the production of bioenergy, potential competition for the land between it and food crops is most prominent (Berndes et al. 2003; Parikka 2004; WWI 2006), and are also highlighted about the nexus of increased land demand with the food production and its effects on food prices (Hoogwijk et al. 2005).

An increased demand of biomass is also expected in Denmark to fulfill its 2050 renewable energy goal (Lund and Mathiesen 2009; Hvelplund et al. 2011). Biomass has a crucial role as the main storable renewable energy sources to complement/supplement the fluctuating renewable sources (Østergaard and Lund 2011). In this situation the challenge is, whether the country should continue relying on its imported biomass or could be self-sufficient in generating sustainable biomass source as well and thus lessening a potential future competition for available biomass resources. This is because, of the total primary renewable energy production of Denmark of 135 PJ in 2011, 31% were imported (Danish Energy Agency 2011). The import share of renewable sources had an increment of 5% from 2010 to 2011 even though the total renewable energy production had merely reduced from 137 PJ to 135 PJ. The average annual increase in the import share of renewable energy in the total primary energy production between the period of 2001-2011 was 19% (Danish Energy Agency 2011). It is thus relevant to assess about the opportunities of utilising domestically produced biomass sources to further strengthen the self-sufficiency in the energy conversions in the country. The relevant biomass resources available in Denmark are reported to be manure, grass, lignocellulosic biomass (e.g. wood and straw) and waste (Tonini and Astrup 2012).

In this context, this research is carried out considering Wheat straw as a fuel input for producing district heat in a Combined Heat and Power (CHP) plant. Wheat straw is selected, because it is the one of the residue of the most common crop, and the crop represents important source for both grain and straw in Denmark (Statistics Denmark 2010). Denmark is the pioneer country in the use of straw in the EU for energy, which is because of dedicated policies, since back from the oil crisis of 1973 (Skøtt and BioPress 2011), and nowadays uses approximately 1.8 Mt (26.1 PJ primary) of straw each year for energy (Giuntoli et al. 2012). Among other biomass sources, some of the strong advantages of wheat straw are such as: it has minimum competition with food and feed industries, and related land use change issues (Fan et al. 2006). In spite of straw thus possessing some advantages compared to other biomass, there are some debates on the crop residue removal from agricultural cropping systems for bioenergy production (Dick et al. 1998; Clapp et al. 2000; Lal 2008). The removal of crop residues for bioenergy production may influence many environmental aspects like N_2O soil emissions, leaching of nitrate, and changes in soil carbon (C) pools (Dick et al. 1998) and on the soil nutrients (Christensen and Olesen 1998).

Biomass conversion can take place through technologies such as direct combustion, thermo-chemical conversion processes (pyrolysis, gasification), bio-chemical processes (anaerobic digestion, fermentation) and physiochemical (chain of biodiesel) in the chain of biomass to energy (McKendry 2002). District heating is the application of a waste heat produced in an energy conversion process, which can be utilised for space heating in building sectors. About 50% of the Danish gross energy consumption of the building sector is occupied by space heating (IEA 2008) and about 60% of the population have access to district heating networks (Dal and Zarnaghi 2009). In this study, CHP plant is considered because power and heat production is one of the important sectors that need to be optimised for fulfilling future energy goals. Furthermore, in 2011 almost 76 % of the total district heat production (132 PJ) of the country are produced from CHP, ranging from large to small and auto producers (Danish Energy Agency 2011). Electricity shares of the thermal production of CHP in Denmark are about 63% (Danish Energy Agency 2011). Biomass (particularly straw) is regarded as a realistic fuel in this sector (Mathiesen et al. 2011).

This refers that heat production is one of the important area that needs to be considered, while diversifying future renewable energy mix of the country. But at the meantime, it is also relevant to consider about the rationale priortisation of biomass such as wheat straw among other available biomasses in the energy conversion processes leading to produce district heat.

1.2. Research Question and Structure

From the discussion carried out in the earlier section, it is revealed that application of crop residues for district heat production could play a coherent role in the course of sustainable energy management goal of Denmark. At the meantime, removal of crop residues has potential impact to the agro ecosystem. Considering these opportunities and limitations, this study considers wheat straw as a feedstock for district heat production and aims to answer the general research question as: *"What are the consequences of utilising wheat straw as a fuel input for producing district heat in a CHP?"*

The research question is further aimed to address the following specific objectives;

- To assess the environmental consequences if wheat straw is considered as a fuel inputs, instead of alternatively ploughing back into soil in the next cropping cycle.
- To assess the environmental impacts, if wheat straw is burnt in a CHP plant to produce district heat
- To assess influences of co-produced electricity in the estimated environmental impacts.
- To compare the environmental performances of straw as a fuel input with alternative fuels such as NG and Wood pellets while producing the equivalent amount of district heat in a CHP.

In addition to four above specific objectives, this study also attempts to assess the economic viability of district heat production.

To answer the above mentioned research questions, the study is structured in five chapters. In Chapter 1, the background of the study and rationality of the study is presented. Literature reviews carried out in Chapter 2 are basically tailored in relation to the scope of the study, and portray about the assumptions relevant for the LCA of district heat production. Literature reviews also provide information about the status of the Danish energy conversions, primarily based on different biomass and in district heat and power production sector. Importance of CHP in the Danish energy scenarios is also briefly discussed. It further discusses the existing scientific body of work within life cycle impact of renewable energy sources. Chapter 3 illustrates the methodological framework, where comprehensive discussions on environmental aspects of evaluating the fuel choices for heat production are carried out, particularly in the frame work of LCA and also discusses about the approaches considered for the economic evaluation. The Chapter also presents the Life Cycle Inventory (LCI) of the biomass conversions and assumptions associated with the processes. Technical scenarios are also presented, which are basically accustomed considering the three different types of fuels to produce district heat, along with three additional sub-scenarios representing the matrix of marginal electricity production. Chapter 4 deals with the results and discussion of the assessment, based on the environmental impact categories considered in the study. Conclusions of the study are presented in Chapter 5, which is further linked with necessary recommendation and future perspectives.

In Appendix 18, a draft version of an article entitled “Life Cycle Assessment of District heat production in a straw fired cogeneration unit and comparison with a boiler” is presented as a supplementary analysis on top of the main objective of the study. In the article, environmental performances of straw fired district heat production in a CHP is compared with a boiler where only heat is produced.

1.3. Study Delimitation

Wheat straw as a fuel alternative can be applied in different ways, such as direct combustion to produce heat and electricity, conversion to gaseous fuels such as methane, hydrogen and carbon monoxide, and conversion to generate liquid fuel through bio refinery concept (Demirbas 2005; Kaparaju et al. 2009). In spite of thus having a number of opportunities on the application of wheat straw as an alternative fuel source, this study is limited with the direct combustion in a CHP. Fuel consumption is also related with the heat transfer through the building envelopes, and a significant amount of fuel can be saved from improved house envelopes increasing the buildings heat efficiency (Joelsson and Gustavsson 2009). This aspect of potential reduction in the consumption of the biomass, particularly from the improved energy efficiency of the building is not considered in the study.

This study has not considered the impacts on the land use changes, because straw is regarded as a residue and minimises the impacts of land use changes, since no additional land is taken into consideration while producing it (Hill et al. 2006; Tilman et al. 2009; Ekman et al. 2013), however land use effects depends on the scale of utilisation of straw, such as for heat/power production, and most importantly its availability (i.e. mass) for doing so. Likewise, this study has not considered other potential applications of the straw, basically straw as a feed material for livestock and as a building material. Consequences of the straw removal for other purposes could have been carried out and compared with the objective set up in this thesis, but this have not been done.

CHAPTER-2: LITERATURE REVIEW

This section is designed to identify the current knowledge within the field. It discusses about the importance of the wheat straw as a fuel alternative in district heat production, and also highlights about the significance of CHP in the energy management perspectives. Information about the production of wheat straw, total primary energy (TPE) production of Denmark, district heat production and the share of biomass on the gross heat production are presented. Furthermore, some fundamental elements of LCA in relation to the scope of this study are reviewed. Finally, a summary on the key understanding to the subject matters in the vicinity of the scope of this study is presented.

2.1. Land cover in Denmark

The total land area of Denmark is 4.36 million ha (Mha), of which the agriculture area represents about 66% (Table 1). 99% of the agricultural areas are classified as arable land, which are dominant with the production of cereal crops representing about 55% of the agricultural areas in 2010 (Table 2).

Table 1: Land Use in Denmark, 2009

Total Area (Mha)	4.36
Artificial Surface (Mha)	0.42
Agricultural land (Mha)	2.89
Forest and semi natural areas (Mha)	0.68
Wet land (Mha)	0.23
Water bodies (Mha)	0.067
Un-classified (Mha)	0.068
Agriculture area (% of total)	66
Arable land (% of agricultural area)	99

Source: (Statistics Denmark 2012)

Areas covered by energy crops in Denmark was 1.6% of the total agricultural area in 2011, and was primarily occupied by Short Rotation Coppice (6292 ha). Only about 93 ha of the area are occupied by other crops. Moreover, Rape seed for oil is grown on about 38980 ha (Dalgaard et al. 2012). Furthermore, in 2010 the total production of straw in Denmark was about 3 million ton (Mt), of which 97% were the residues from cereal crops (Statistics Denmark 2012).

Table 2: Crops coverage of the total agricultural land in Demark

Crop coverage	2008	2009	2010
Total Agricultural area (Mha)	2.67	2.62	2.65
	percent		
Cereals	56.4	55.7	55.5
Pulses	0.2	0.2	0.4
Root crops	3.1	3.1	3.1
Seeds for industrial use	6.5	6.2	6.3
Seeds for sowing	3.1	3.4	2.5
Grass and green fodder in rotation	19.3	20.4	21.2
Horticultural products	0.8	0.8	0.8
Other crops	9.8	7.5	7.9
Permanent grassland	0.8	2.7	2.3
Set aside	2.6	0.2	0.4

Source: (Statistics Denmark 2012)

2.2. Straw Production and Utilisation in Denmark

According to the agricultural statistics of Denmark, the area covered by cereals is not consistent (Table 3), where in the year 2011 and 2010 the area covered was 1.48 Mha and 2.65 Mha respectively. In 2011, wheat covered 50% of the Cereal area. The total straw production was from the area of 0.996 Mha, with the productivity of about 3.29 t/ha of the straw production area (Table 3).

Furthermore, energinet.dk (2012) reported that between the period of 1997 to 2006, straw production in Denmark ranged between 5.2 and 6.8 Mt per year, while the amount used for energy varied between 1.0 and 1.5 Mt. Likewise, the annual average straw production in Denmark for the period of 2004-2008 was 5.5 Mt. Of this average annual production, 3.4 Mt is reported being used in agriculture and for energy purposes, which indicates that for the period the annual amount of the surplus straw was about 2.1 Mt (Skøtt and BioPress 2011).

Table 3: Straw Production area and productivity in Denmark

		2000	2005	2009	2010	2011
Cereals	Area, ('000 ha)	1514	1509	1488	1484	1484
Wheat	Area, ('000 ha)	628	676	739	764	747
Winter wheat	Area, ('000 ha)	619	664	729	750	727
Spring wheat	Area, ('000 ha)	8	12	10	14	20
Straw (Total)	Area, ('000 ha)	981	964	1068	1008	996
	Production (Mt)	3.70	3.25	4.05	3.31	3.27
	Average Yield (t/ha)	3.77	3.37	3.79	3.28	3.29
Straw (Cereals)	Straw Cereals ('000 ha)	965	951	1025	975	962
	Average Production of straw (cereals) (Mt)	3.64	3.21	3.89	3.20	3.16

Source: (Statistics Denmark 2012)

2.3. Characteristics of Straw as an energy source

The physical properties (moisture content, particle size, and bulk density) of a biomass, such as wheat straw greatly influence the design and energy conversion systems. High moisture content decreases the heating value of fuel, which lowers the conversion efficiency as a significant amount of energy would be used for drying of the biomass (Mansaray and Ghaly 1997). The energy conversion efficiency, through the direct combustion is also determined by the particle size distributions, as it influences the flow ability, heating, diffusion and rate of reactions during the conversion process (Hernández et al. 2010; Guo et al. 2012). The bulk density is important as it influences the economics of collection, transportation and storage as well as feeding the material into the thermo-chemical conversion system (Natarajan et al. 1998).

The dry matter (DM) content of straw suitable for combustion is reported to be 85% (Nielsen 2004), and the lower heating value is about 14.5 MJ/kg (Skøtt and BioPress 2011; Schmidt and Brandao 2013). The DM is constituted of about 47.3% Carbon, 5% Hydrogen, 37% Oxygen as well as small amounts of Nitrogen, Sulphur, Alkali, Chloride and other (Møller et al. 2005). Aggressive components contained in straw, such as chlorine, is regarded prone to rapid formations of deposits and risks of slagging and corrosion in the boiler (Kargbo et al. 2009; energinet.dk 2012), which retards the heat transfer. Similarly, the slag formed on the furnace and on the grates hinder fuel feeding, combustion and ash handling processes

(Jenkins et al. 1998). But, recent advances in the material design and production of furnaces have resulted with fairly high steam data and thus efficiencies (energinet.dk 2012).

Pretreatment of straw is normally carried out to remove problematic compounds such as chlorine and alkali (Skøtt and BioPress 2011), and also to improve both physical and chemical properties of the biomass, thereby minimizing the costs of transport, handling and storage. It is also useful for improving combustion efficiency and reducing emission. However, the pretreatment technologies must be especially efficient to compensate for the costs involved in straw collection, transport, hand transport, handling and storage (Kargbo et al. 2009). It is also found that mostly straw are allowed to remain on the field for some days or weeks, exposed to rain (thereafter denoted 'grey straw'), and is allowed to dry again, which wash away many problematic compounds (Skøtt and BioPress 2011). Straw is often delivered as big rectangular bales, approx. 5-700 kg each, from stores at the farms to the desired power plants (energinet.dk 2012).

The properties of the straw relevant for the LCA is further described in Section 3.5.

2.4. Primary Energy Production in Denmark

This section focus on the rationality of considering the straw for district heat production, where the Danish status of TPE production, energy mix in electricity production, contribution of biomass in the TPE production in different years are discussed. This further connects with the advantages of CHP, primarily the simultaneous production of heat and electricity.

The TPE production of Denmark in 2011 was 887 PJ, where the share of crude oil was 53%, followed by NG with 30%, renewable energy with 15% and waste (non-renewable) covered 2%. When we look into the changes in the use of different energy input in the total primary production, between the period of 2000-2011, crude oil and NG consumption has decreased by 38% and 15% respectively, and the increase in the waste (non-renewable) and renewable energy based production was 27% and 76% respectively (Danish Energy Agency 2011). Between the periods of 2000-2011, the primary energy production has also decreased by 24%. This makes biomass even more important as it is not only for environmental reasons but also for self-sufficiency reasons.

Of the 135 PJ TPE produced from renewable energy sources in 2011, biomass had the largest share at 62%. Firewood and (renewable) waste were the largest source of biomass in the TPE production, covering 25% each in the share of biomass energy in 2011. Straw covered 24% of the TPE production based on biomass, and rest were covered by woodchips (14%), wood waste (9%), wood pellets (3%), and bio-oil (1%). Straw has been found covering 24% of the biomass share in the TPE production (Danish Energy Agency 2011).

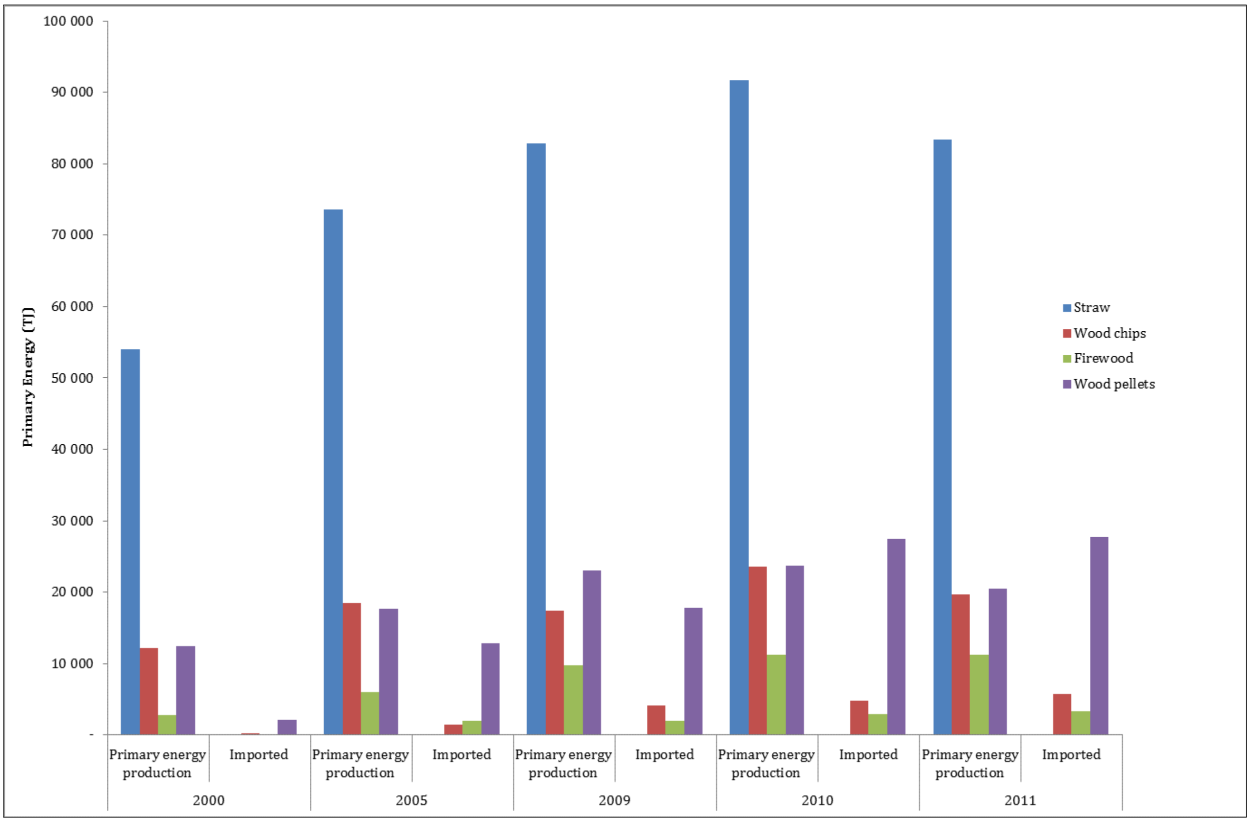

Figure 1: Shares of imported biomass of the total primary energy produced from the respective biomass sources.
Source: based on Danish Energy Agency (2011)

The share of renewable energy of the TPE production in 2011 has increased almost two fold compared to 2000. Furthermore, of this total renewable energy production, in 2011 31% are based on the imported sources, which was only 3% in 2000 of the total renewable energy production. Most interesting picture is revealed when the primary energy production for the period of 2000-2011, based on biomass sources (in particular firewood, Wood pellets and wood chips) is further analysed. During this period, almost all the biomass are imported at an increasing rate, whilst straw has been one of the domestically produced source of biomass energy (Figure 1).

All these changes in the energy mix, shows that biomass is one of the important source of energy for fulfilling the higher shares of renewable energy in the future primary energy production and consumption. In spite of this, it may be important to ensure the self sufficiency of the biomass in the course of sustainable energy management and also to fulfill the Danish 2050 renewable energy goal.

2.4.1. Fuel Mix in heat and power production

Figure 2 shows the status of consumption of major fuels, such as NG, coal, and biomass, in the district heat production in Denmark. It is found that of the gross district heat production in 2000 and 2011, coal and NG consumption has decreased from 32% to 23%, and 35% to 26% respectively. For the same period, consumption of straw has merely increased from 5% to 7%, whilst wood has increased from 4% to 19% (Danish Energy Agency 2011).

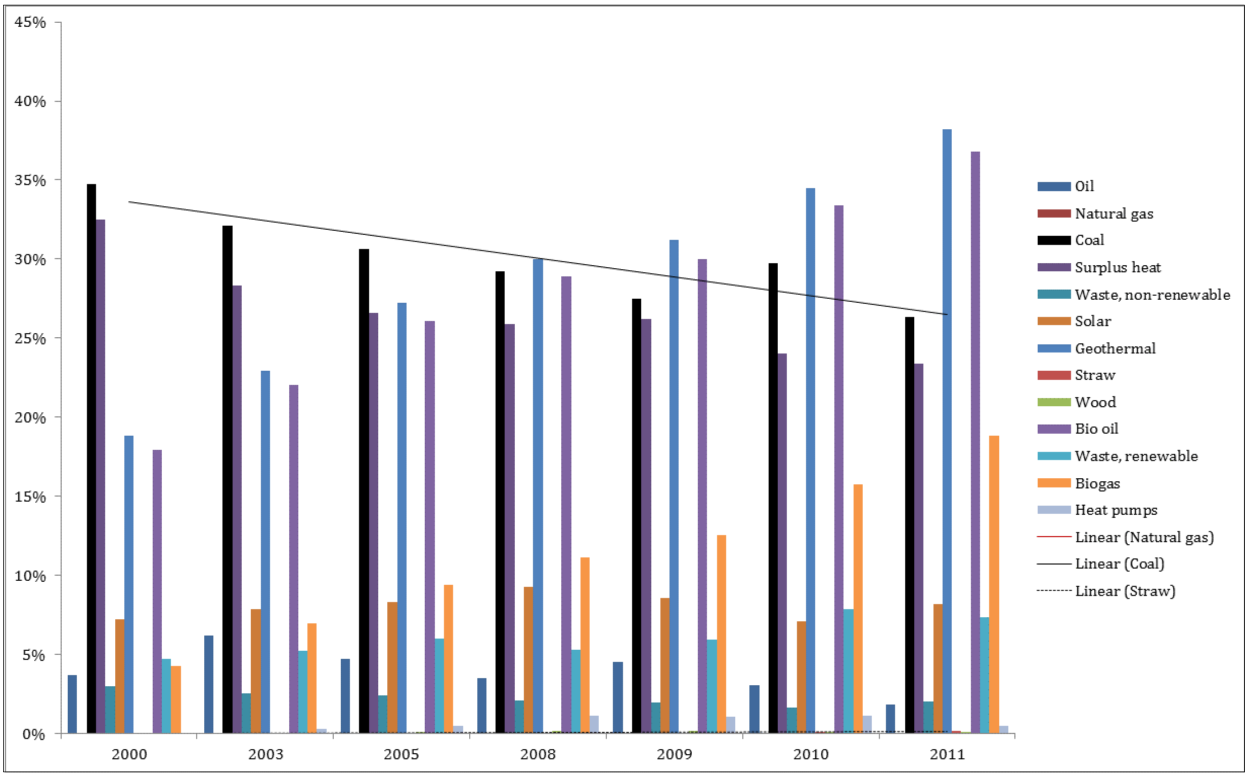

Figure 2: Status of fuel Mix in the gross production of district heat in Denmark
Source: based on Danish Energy Agency (2011)

Likewise, the status of fuel mix in the Danish electricity production reveals that coal and NG are the dominant fuel, where in 2000 of the total electricity production (277 PJ); consumption of coal was 48% and has marginally reduced to 46% in 2011. Likewise, NG consumption in 2000 and 2011 were 25% and 17% respectively of the total electricity production. In the stake of biomass source, straw and wood are the major fuels. In 2000, straw and wood consumption were 1% each, which were increased to cover 3% and 8% respectively of the total electricity production in 2011 (Figure 3).

The import shares of biomass as shown in Figure 1 also motivates to investigate on the possibilities of utilising domestic production, primarily agricultural residues such as straw in energy conversion systems. It is also relevant from the life cycle point of view, if impacts due to transportation of such imported biomass are also analysed. For e.g. Schmidt and Brandao

(2013) reported that in 2010, Denmark imported 1.6 Mt of wood pellets, of which about 40% came from the Baltic countries (such as Latvia), where the transport by (freight ship from Latvia) to Denmark is about 845 km (Ecoinvent Centre 2010).

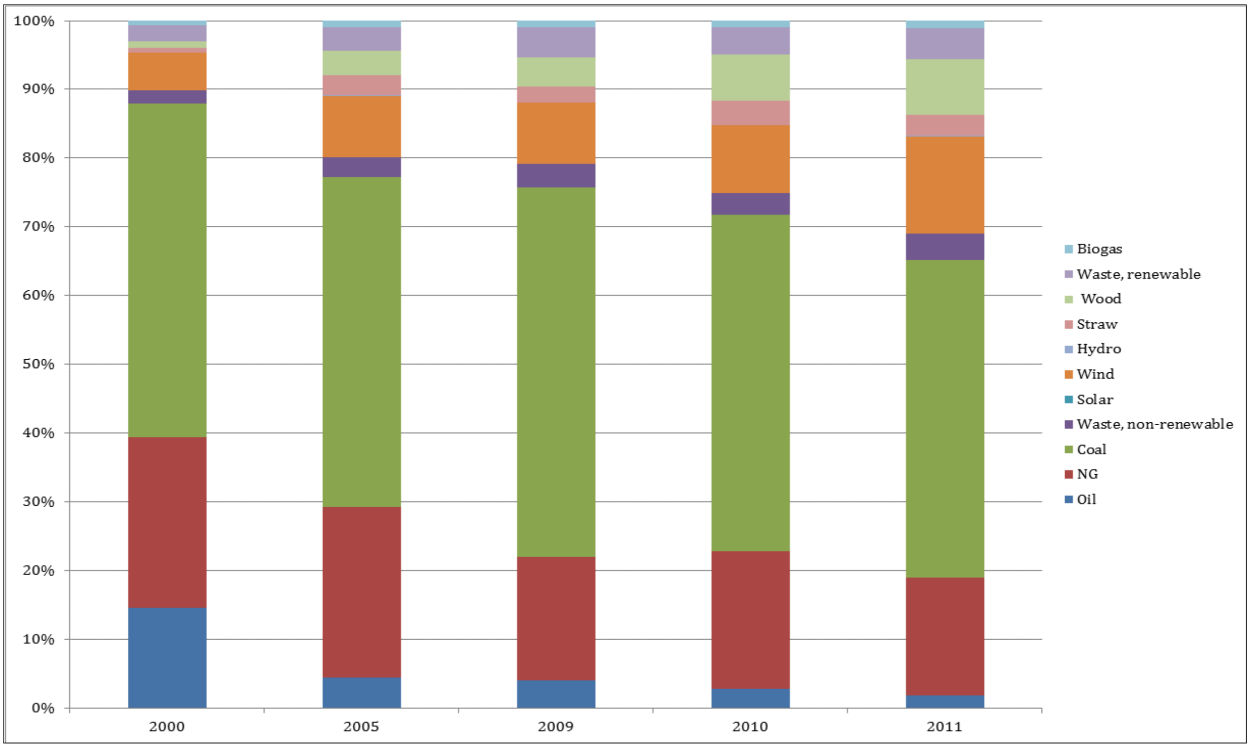

Figure 3: Fuel Mix in total electricity production, Denmark
Source: based on Danish Energy Agency (2011)

Furthermore, Forsberg (2000) analysed the supply chain of biomass, in particular bales or pellets, originating from the tree sections or forest residues, transported from Sweden to the Netherlands. The biomass analysed was primarily used for electricity production. The same study reported that the emissions associated with the transportation of biomass in a local market have a significant importance compared to long range transportation, performed with ships. The study further highlighted that the use of fuels and electricity for operating machines and transportation required energy corresponding to about 7–9% of the delivered electricity from the system.

Skøtt and BioPress (2011), reported that around the year 2000, many Danish farmers decided to replace the straw in boilers with wood chips, which was due to the reduction in the wood chip prices, primarily because of extensive import of wood chips from the Baltics. After the trading of straw was initiated on the free market through the competitive bidding, it has been regarded a competitive forms of fuels, which resulted to the expansion of straw fired heating plants again in Denmark.

2.4.2. Combined Heat and Power Plants in Danish energy system

Denmark has been found successful in stabilising its primary energy supply from the last three decades (Lund 2005; Parajuli 2012). Expansion of CHP in the overall energy production and supply, along with the insulation of houses has led to decrease in fuel consumption for domestic heating in the country (Lund 2005; Østergaard 2010). This also has a determining role in strengthening the bondage of primary energy needs of the country, through simultaneous heat and electricity production (Østergaard 2009). This fundamental importance of CHP in the context of Denmark can be visualised from its contribution to the gross district heat production and electricity in association with the thermal production of these technologies (Figure 4). For e.g. in 2011, the share of CHP in the district heat production is 76% and the electricity share of this thermal production is 63%.

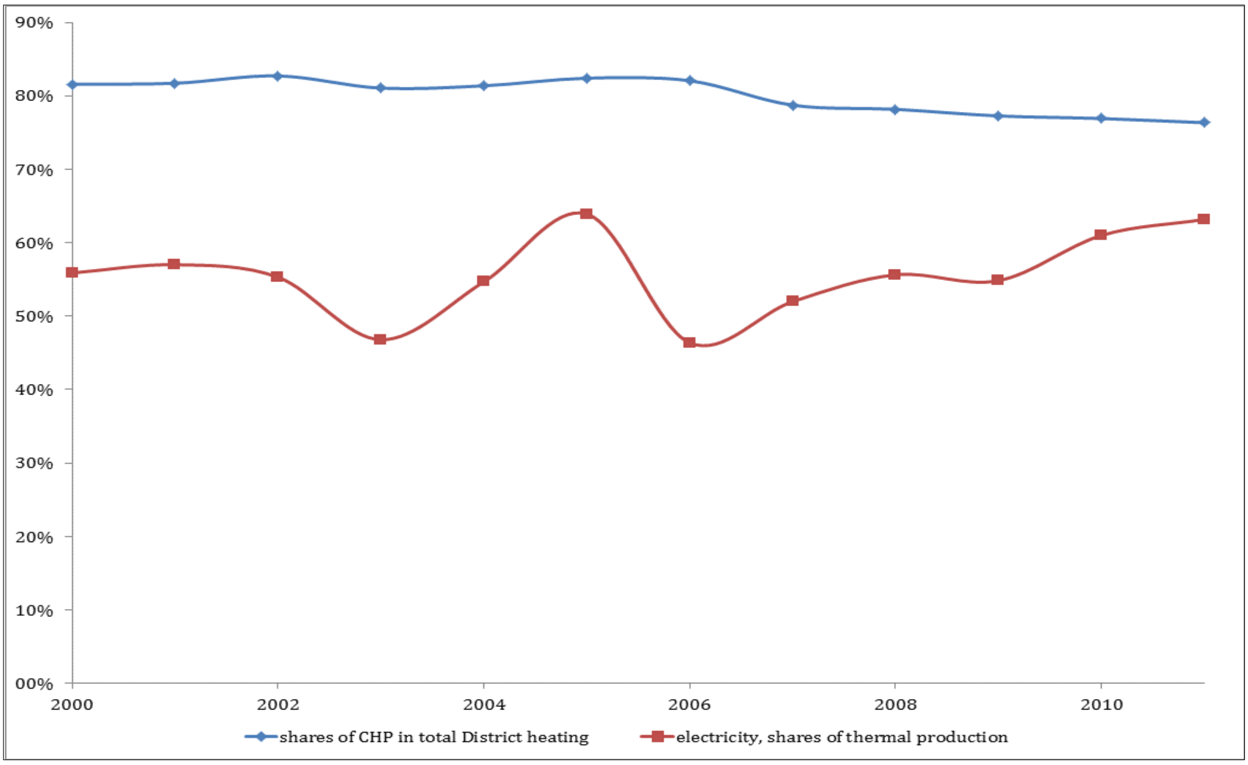

Figure 4: Shares of CHP in gross district heat and electricity production
Source: based on Danish Energy Agency (2011)

The importance of CHP in the energy system are including, its contribution to the optimisation of total energy costs, capacity and societal costs, reduction in the fuel consumptions, CO_2 reductions, and more importantly ensuring the back-up of the heat produced as a thermal storage and simultaneous electricity production (Østergaard 2009). Hence, in this thesis CHP is considered as a combustion element in the life cycle assessment process.

2.4.3. Marginal Electricity Production

The main product considered in this study is the heat and electricity is assumed as a co-product. It is thus relevant to identify the marginal technology of electricity in the market, which is going to be affected because of the co-produced electricity from the biomass based CHP plant. Technologies which are actually affected by the small changes in the demand while carrying out comparative LCA are defined as marginal technologies (Weidema et al. 1999).

Despite this necessity, there are a number of uncertainties in the selection of marginal technologies (Mathiesen et al. 2009). The uncertainties are primarily defined from the perspectives such as; temporal and long term effects of substitution (Weidema et al. 1999; Ekvall and Weidema 2004), market segment of the products and competing alternatives (Ekvall and Weidema 2004), and cost efficiency (i.e. if demand is decreasing at higher rate than the investment in the alternatives, marginal technology is the one with highest short term cost, and if the demand is decreasing at a lower rate than the rate of investment then the marginal technology is with the lower short-term cost) (Mathiesen et al. 2009). Similarly, country specific constraints such as, limits of natural resources, emission limits, emission quotas, may influence the selection of technologies/fuels as a marginal substitution, for e.g. in most of the EU countries, lignite based power plants were no further considered active player in the electricity market (Weidema et al. 1999). Weidema et al. (1999) have further reported that due to lower capital cost, NG based power plants were regarded as marginal technology in the Nordic electricity market. In the context of Denmark, historical trend of electricity mix and future energy marginal cost of power generation have been found considered for identifying marginal technologies (Mathiesen et al. 2009). According to the official Danish energy policies of 2003, where fuel prices were relatively lower than today, NG based power production was considered as the marginal technology. Whilst, as per the 2005 energy policy, which had CO_2-quota prices included on top of the three different fuel prices, wind power was identified as the marginal technology. This was considered expecting that the technology will have lowest long-term cost beyond 2020 and except in the condition where fuel prices and CO_2-prices are lower (Mathiesen et al. 2009). The Danish energy projection till 2025 has made a prediction that there will be moderate rises in oil prices and in CO_2 allowance prices, which will increase the share of renewable energy to electricity supply by more than 36% in 2025, and expected to be primarily based on Wind power (Ministry of Transport and Energy 2005). But, Mathiesen et al. (2009) further indicated that since wind power cannot respond to changes in demand and as its potential is constrained from one region to another, it cannot be regarded as marginal technology. Lund et al. (2010) reported that based on a business-as-usual energy projection to year 2030, as presented in Ministry of Transport and Energy (2005), and the annual average marginal on an hourly basis, NG based power plants can be considered as a marginal technology.

Considering these arguments, this thesis has considered substitutable marginal electricity production separately as NG, coal and Wind power based electricity production (see section 3.5.4).

2.5. Life Cycle Assessment

LCA is the approach of undertaking systematic investigation on the use of available resources adequately considering the environmental aspects of the products/system and its potential impact throughout the products/system life (ISO 1997). It is often referred as 'cradle to grave' perspective of looking into resource utilisation, which enables us to avoid the sub-optimisation that may result in the case if only a few process are being focused(Pehnt 2006). The process of undertaking LCA begins with defining goal and scope, leading towards inventory analysis, impact assessment, and interpretation of results (Guinee 2002; Rebitzer et al. 2004). One of the important application of LCA is; its ability to present the net energy analysis of the products/system (Huettner 1976). For instance, any particular new technology can be disregarded in the energy generation system, if it consumes more energy than it produced, leading to negative net energy output. Furthermore, Mortimer (1991) has also highlighted that a new technology can be regarded as potential choice, if could achieve positive net energy output, when energy is in short supply, despite of it being found economically unfavourable. LCA of energy products/system facilitates to look into its whole chain/components, including all energy and material flows. The life cycle impact of typical renewable energy systems is important when comparing them to conventional fuel-based systems for rational choice of energy sources (Sørensen 1994).

Due to limited studies in respect to heat production, reviews are presented from the perspectives of biomass cultivation and electricity production from biomass and other renewable energy technologies.

2.5.1. NRE Use

Heller et al. (2003) has indicated that while producing dedicated biomass energy, such as willow in New York, non-renewable energy use is 0.018 MJ per 1 MJ energy content of the biomass. Furthermore, with the considerations of transportation and energy conversion efficiency, the NRE use per 1 kWh of electricity produced is 0.33 MJ. Ericsson et al. (2006)

further presented the economic view point in the context of growing willow in Europe, where they discussed that biomass, such as Willow perform much better in terms of energy than annual food crops. Similarly, it is found that Willow production has a high net energy output compared to such as grain and oil seeds production, and its biomass yield is relatively high (Börjesson 1996).

Blengini et al. (2011) have further reported that to generate 1 MJ of electricity/heat, NRE use are found in the range of 0.2-0.3 MJ, while using promising energy crops such as Maize, Sorghum, Triticale and Miscanthus mixed with cow manure in a biogas plant. The ranges are due to the consideration of different co-products in the system (Blengini et al. 2011).

2.5.2. Soil carbon sequestration and effects of crop residues removal

In general, organic carbon (C) is stored in different pools such as above and below ground residues, dead wood, litter and soil (Gregorich et al. 1996; Cherubini and Strømman 2011). Changes in the land utilisation also bring changes in the C pool storages (Johnson 1992; Cherubini and Strømman 2011), until a new equilibrium is reached, which have significant impact in the greenhouse gas (GHG) balance (Cherubini and Strømman 2011). For e.g. as a soil organic carbon (SOC), where larger quantities of these storage occurs, even relatively small changes in their amount can have impact in the GHG balance. Righelato and Spracklen (2007) reported that land used to store carbon in forest would sequester 2-9 times more carbon over a 30-year period than the emissions avoided by the use of biofuel grown on the same land. Bird et al. (2008) further highlighted that the preference on bioenergy crops also depend on the various key factors such as yield of biomass, conversion efficiency compared to fossil fuel, and the time frame of substitution taking place, which has a direct and indirect relation with the land use and potential changes with it. Effects of crop residue removal are generally linked with the consequences such as limiting the soil C sequestration potential (Wilhelm et al. 2004; Lal 2005; Lal 2008). Harvesting of all crop residues possess a threat to an agro-ecosystem (Pimentel et al. 1995; Pimentel and Kounang 1998; Wilhelm et al. 2007; Gomiero et al. 2010). For e.g. N_2O soil emissions, leaching of nitrate and changes in soil carbon pools (Christensen and Olesen 1998; Lal 2008; Cherubini and Strømman 2011) are the most common threats.

The changes in the soil C is dependent with the time as the amount of C release to atmosphere in the form of Carbon dioxide (CO_2) is varied with the time horizon. Figure 5 shows about the impact of choosing different time frame for estimating the soil C changes. The rate of soil C changes with the application of crop residues or manure to the soil is higher in the first few years and decline in the subsequent years (Petersen et al.). This tendency of changes in the soil C pool is further illustrated in Figure 6, where it seen that the variation in the Soil C retention potential after the application of crop residues or manure to a soil. The release of Soil C to the atmosphere is lower in the first few years than the following years, which leads to have more C retention in the soil in the beginning and gradually decline as time proceeds (Petersen et al.).

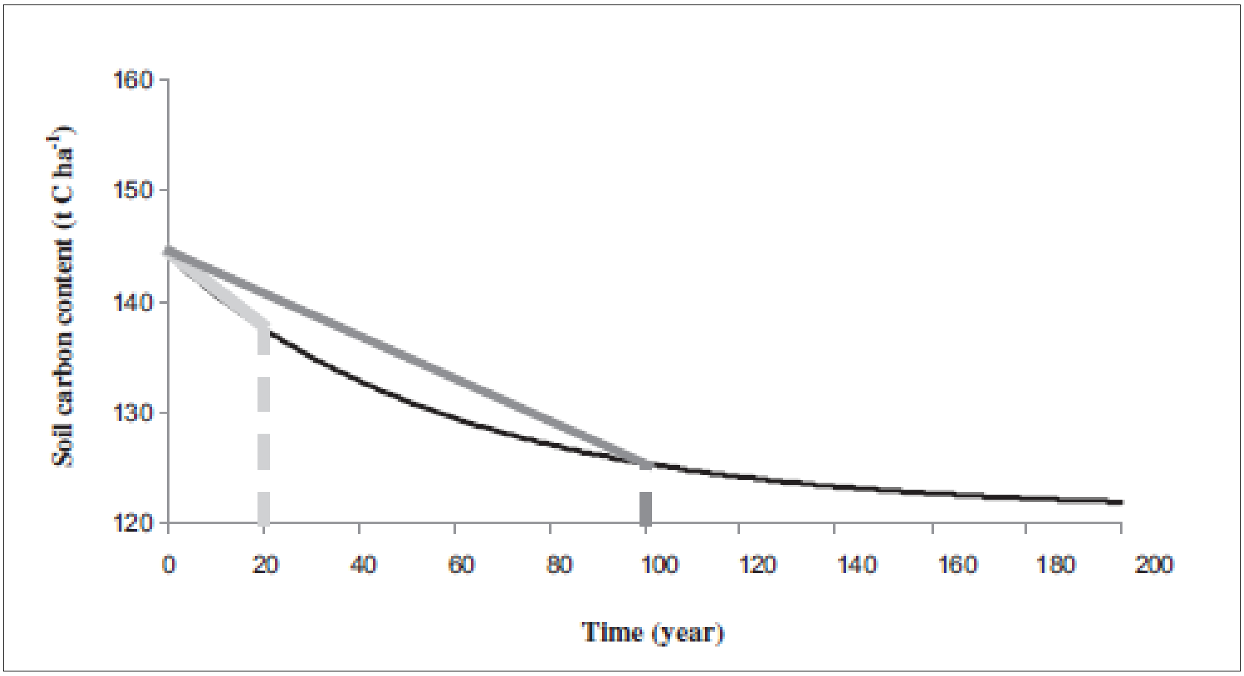

Figure 5: Impact of the time on estimating soil C changes
Source: adapted from (Petersen et al.)

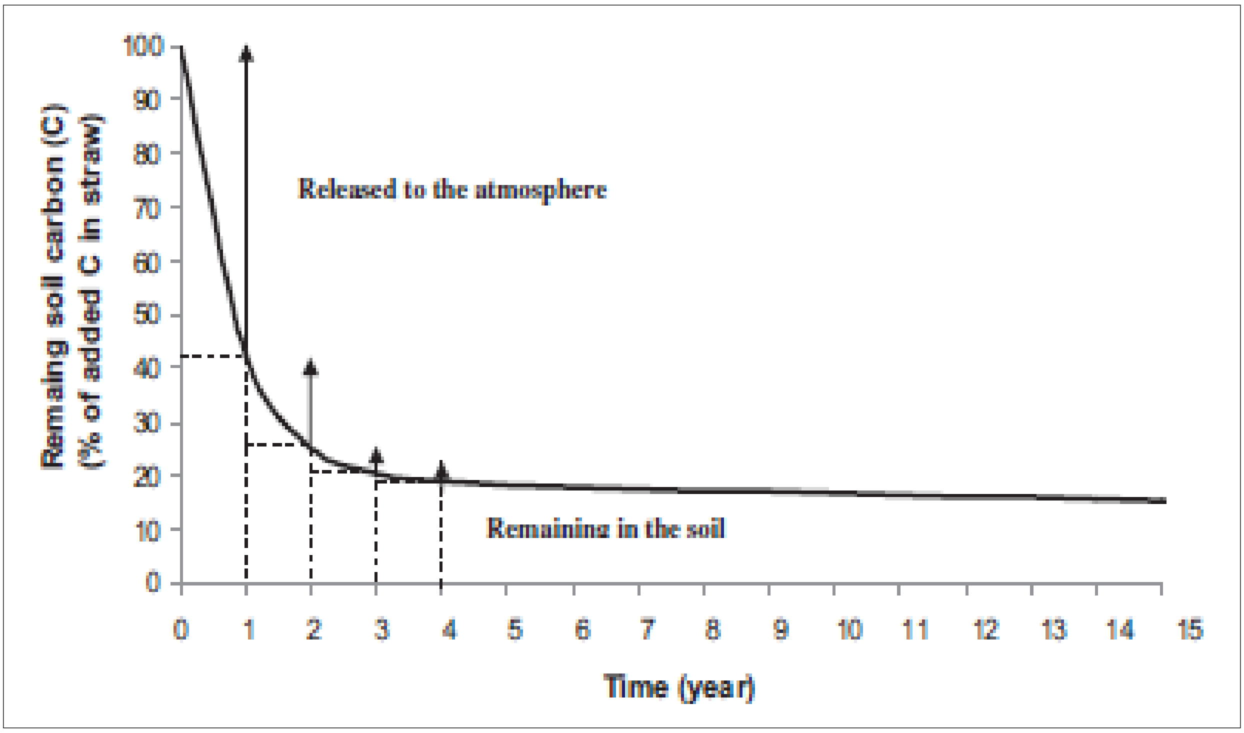

Figure 6: Time based decay of C from application of crop residues/manure to the soil
Source: adapted from (Petersen et al.)

This indicates that if 1 t of straw is burnt at year zero (in reference to Figure 5-6), most of the Carbon is released to the atmosphere; otherwise if remained in the field would lead to have higher sequestration.

Considering the tendency of soil C variations, the time based soil C sequestration potential from the decay of straw is also reviewed, on which Petersen and Knudsen (2010) reported that 1 t of straw corresponds to 79.6 kg soil C sequestration (i.e. 19.8% of total C in straw) and 8 kg soil N build-up in a 20-year time frame, based on a loamy soil for Danish Climatic condition. Similarly in the same study, the soil C sequestration is reported to be 8.8% of the total C content in 1t of the straw, which further correspond to 3.53 kg soil N-buildup, in a 100-years perspective. The corresponding soil N-buildup is with respect to Carbon-nitrogen ratio of 1:10 (Petersen and Berntsen 2003). Hence, if straw is removed from the field, the above mentioned soil C and N buildup is restricted.

The life cycle impact of removal of wheat straw is further described in section 3.3.1.

2.5.3. Efficient Application of Biomass

It is becoming increasingly important for policy makers to understand about the questions associated with the utilisation of agricultural residues and cultivation of energy crops (EEA 2006; WWI 2006; COM 2007), from the perspectives of land use, energy intensity, and GWP. There are some studies, which have made comparison on the alternatives of biomass utilisation for energy purposes. It is essential to make an appropriate selection for the best utilisation of biomass from the standpoint of GHG emissions, which is primarily based on the assumption that competition for biomass while fulfilling sustainable energy demand is unavoidable (Botha and von Blottnitz 2006; Searcy and Flynn 2008; Uihlein et al. 2008; Cherubini et al. 2009). In the same studies, it has been highlighted that selection should ensure whether biomass would be used for direct combustion, such as in CHP, or have to be regarded as principal feedstock for transport fuels production.

Concawe et al. (2007) concluded that biomass use for electricity production enhances larger GHG savings, especially when compared to first generation biofuels. Searcy and Flynn (2008) showed that while producing electricity from unit input of biomass such as agricultural residues, through the processes such as direct firing or gasification, can save about three times the amount of GHG emissions, compared to the amount saved by bioethanol and Fischer–Tropsch diesel (i.e. production from switch grass via gasification of biomass). In this comparison, marginal substitution of electricity is based on coal. Furthermore, Cherubini et al. (2009) and Kaltschmitt et al. (1997) have reported that greater GHG savings per hectare of land can be made from the utilisation of biomass for heating applications, compared to the conventional biofuels and bioelectricity production systems. Similarly, Botha and von Blottnitz (2006) have reported that in the conversion of bagasse to either electricity or bioethanol, electricity was found favourable when energy, GHG, eutrophication and acidification indicators are considered, whilst bioethanol production was preferable if indicators such as resource depletion and toxicity concerns are considered.

Likewise, for generating unit electricity, biomass such as willow and hybrid poplar are considered more favourable if their high yield is compared to food crops like corn and soybean, and also if their residues are not harvested. Moreover, electricity generation from the former is less efficient than converting the latter to ethanol through ‘‘biorefinery’’ process. It has been found that biomass power plants convert only 23–37% of biomass energy content into electricity (EPRI 1997; Mann and Spath 1997), while ethanol contains 53–56% of biomass energy content (Marland and Turhollow 1991; Kim and Dale 2005; Pimentel and Patzek 2005). In addition to the crop land, a biomass power plant requires 7–11 m^2/TJ of direct land area assuming a lifetime of 30 years (Mann and Spath 1997; Pimentel and Patzek 2005).

2.6. Fuel economics

In Denmark the fuel prices are determined by a number of important factors such as economic and environmental regulations (energy taxes, CO_2 taxes, CO_2 quotas etc) (Ea Energy Analyses 2010). In the case of heat production energy taxes are generally employed to the fuel, whilst for electricity production it is allocated on the end-users (Ea Energy Analyses 2010).

The Danish heat production related applicable taxes for 2010 shows that the energy tax for both coal and NG was 57.3 DKK/GJ. In the same year, the CO_2 tax was 14.8 DKK/GJ on coal, and 8.9 DKK/GJ on NG. Likewise, for coal and NG the CO_2 allowances (quotas) amounts to about 22.6 and 13.6 DKK/GJ respectively (Ea Energy Analyses 2010). Biomass sources are exempted from these taxes, which is the main reason that biomass consumption in the Danish heating sector is popular (Ea Energy Analyses 2010). Figure 7-8 shows about the influences of additional taxes to the fuel prices in Denmark, where in the absence of taxes and subsidies, the most attractive fuel is coal (Figure 7), which has an insignificant growth in the prices over the next two decades.

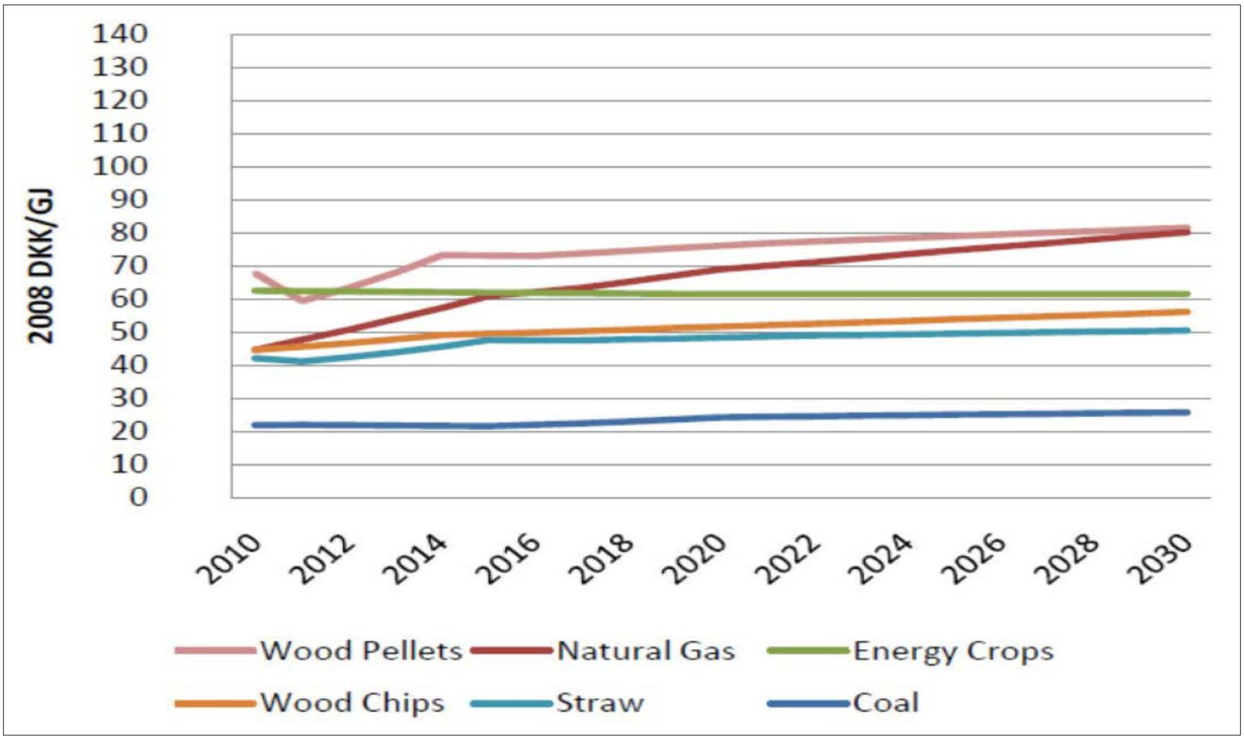

Figure 7: Danish Energy Association forecasted fuel prices for CHP production, exclusive VAT
Source: adapted from Ea Energy Analyses (2010)

The forecasts of the Danish Energy agency on the straw price in the year 2008 is moderately increasing from 37.8 DKK/GJ to 42.2 DKK/GJ in 2015 and 44.1 DKK/GJ in 2025. The price for wood pellets in 2008 lies between 60 and 80 DKK/GJ depending on the quality and transportable distances, and the prices are considerable higher than for other biomass fuels. The Danish energy agency expects its prices to increase from 67.7 DKK/GJ to 71.3 DKK/GJ in 2015 and 77 DKK/GJ in 2025 (all prices in 2010 DKK). If energy and CO_2 taxes are included in the normal fuel prices, the most expensive fuel among other fuels seems to be NG, followed by Coal and rest by biomass sources (Figure 8). The projections of these fuels prices, which include the taxes, are shown in Figure 9.

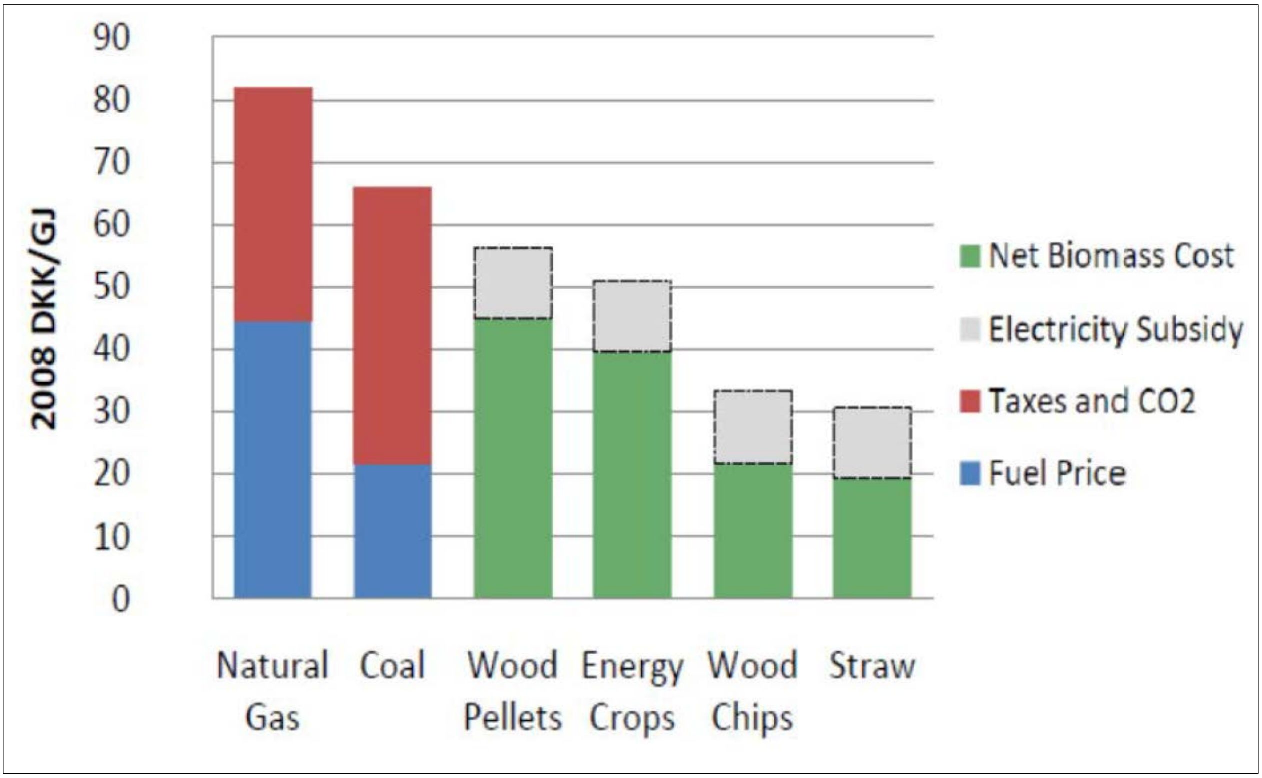

Figure 8: Role of CO_2 prices, energy taxes, and subsides on fuel costs in Denmark for a CHP plant

Source: adapted from Ea Energy Analyses (2010)

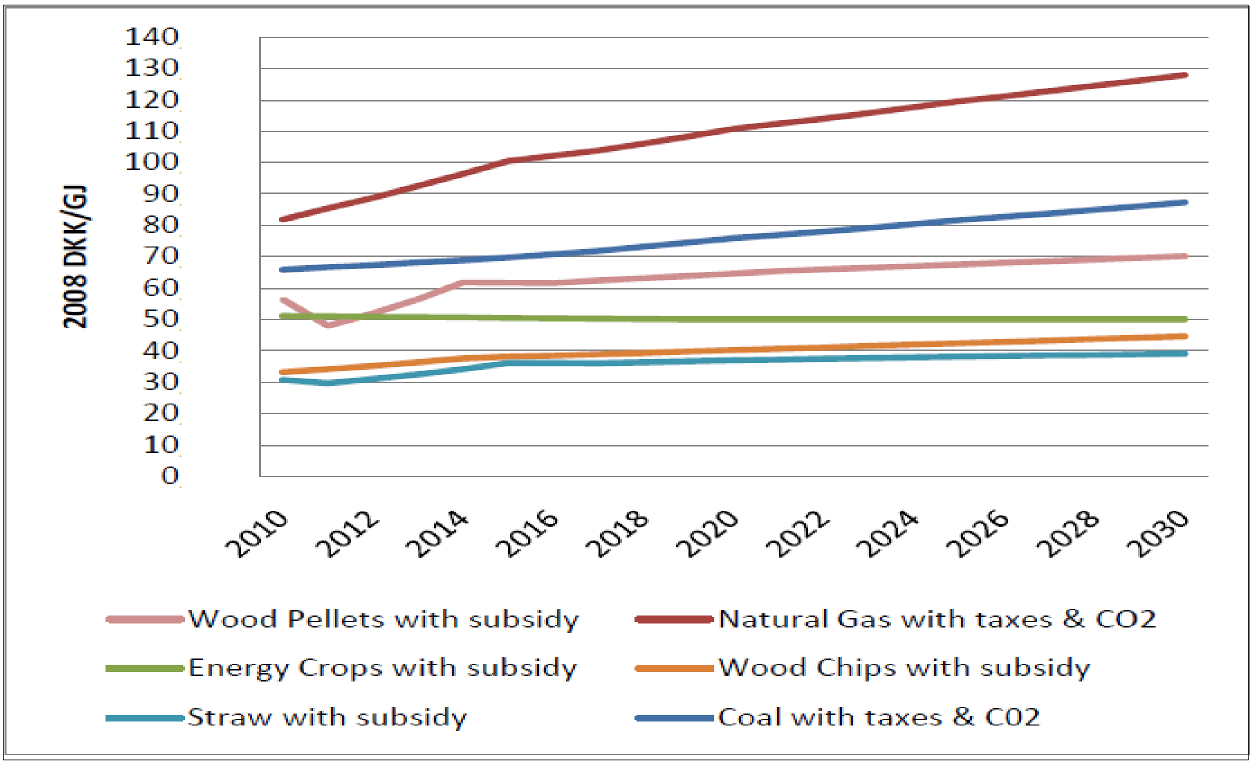

Figure 9: Projected Fuel prices, including taxes (excluding VAT)

Source: adapted from Ea Energy Analyses (2010)

2.7. Sumarising the Literature Review

From the literature review, the use of bioenergy are summarised in following perspectives, outlining the opportunities and issues associated within the use.

Energy Diversification and District Heat

- Biomass is increasingly popular in the district heat production in Denmark, covering about 28% of the annual average amount of the total gross district heat production from the period of 2000-2011 (Danish Energy Agency 2011).
- It is also reported that if the extensive use of the available land for agricultural purposes is considered, biomass resources can be regarded insignificantly limited (Østergaard et al. 2010). But, while fulfilling the higher penetration of renewable energy in the country, biomass is also regarded as a storable renewable energy, and is important in conjunction with fluctuating renewable energy system (Hvelplund et al. 2011) .
- Of the total renewable energy production for the period of 2000-2011, the annual import shares of renewable energy sources was 19%. Import share was maximum in 2011 with 31% and lowest in 2000 with 3% of the total renewable energy production of the respective years (Danish Energy Agency 2011).
- NG, Coal and Wind power based electricity production can be regarded as the marginal electricity production technologies, which has been assumed to be substituted by the co-product of the cogeneration unit assumed in this thesis.
- Biomass such as firewood, wood chips and wood pellets are among the renewable energy sources, which are primarily imported (Figure 1).
- Biomass is one of the important fuel source considered for fulfilling the 2050 renewable energy goal of the country (Lund and Mathiesen 2009; Hvelplund et al. 2011). The recent “Ten-million-tonnes plan” of Denmark has also highlighted on this aspect and is aimed to significantly increase the bioenergy and biomass harvest, as 10 million ton per annum (Dalgaard et al. 2012).

Life Cycle Considerations

- It is important to investigate prevailing issues, raised in the socio-political context on the potential competition among biomass sources, as well as with other uses such as food (Berndes et al. 2003; Parikka 2004; WWI 2006).

- It is also found that the environmental performances of selecting renewable energy sources depend on the potential fuel, which is going to be substituted (Botha and von Blottnitz 2006; Searcy and Flynn 2008; Uihlein et al. 2008; Cherubini et al. 2009).
- The environmental performances of selecting biomass sources also depend on the application or conversion modes of the biomass (direct combustion, anaerobic digestion and thermo-chemical conversions) and conversion efficiency as presented in studies such as (Mann and Spath 1997; Pimentel and Patzek 2005).
- Transportation also plays significant role, while selecting a particular biomass among different sources, if the overall environmental performances such as NRE use and GWP in the process of transportation are accounted.
- Bioenergy crops offer favourable results in the context of LUC and iLUC, if cultivation is normally carried out on marginal or degraded land (Spatari et al. 2005; Styles and Jones 2007; Cherubini and Jungmeier 2010). Consideration of crop residues since does not demand for the additional agricultural land, it does not have considerable effects on the land use changes, provided that amount of residues to be harvested are limited (Hill et al. 2006; Tilman et al. 2009; Ekman et al. 2013).
- Crop residue removal for energy purpose may have impact on the SOC, leaching of nitrate and reduction in the soil fertility (Christensen and Olesen 1998; Lal 2008; Cherubini and Strømman 2011). This further highlights that if crop residue is to be removed, the equivalent quantity of nutrients, which are normally available from the residues should be compensated by externally adding to the soil (Nguyen et al. 2013).

Hence, in order to identify the better environmental performances, for instance, savings in energy and emissions, from any type of bioenergy production and use, a thorough evaluation from ‘cradle to grave’ must be carefully carried out. LCA is thus has been the method to assess the overall impact of resource utilisation.

This chapter discusses about the goal and scope of the LCA carried out in this study. A system boundary in relation to the energy conversion processes of the wheat straw to produce district heat in a CHP is presented. Life Cycle Inventories (LCIs) are also presented with respect to the reference flow of the fuel inputs. Approach of undertaking investment analysis on the production of district heat is also discussed.

3.1. Goal and Scope definition

The goal of this study is to assess the environmental consequences of using wheat straw for district heat production in a CHP. In addition to this goal, the study also assesses the environmental performances of producing heat in a NG and Wood pellet fired CHP plant. Environmental performances are assessed in terms of impact categories such as; GWP, NRE use, AP, EP (aquatic) and EP (terrestrial).

3.2. System Boundary Definition and Functional Unit

The system boundary presented in Figure 10 illustrates the energy conversion process of wheat straw, to support the main objective of this study.

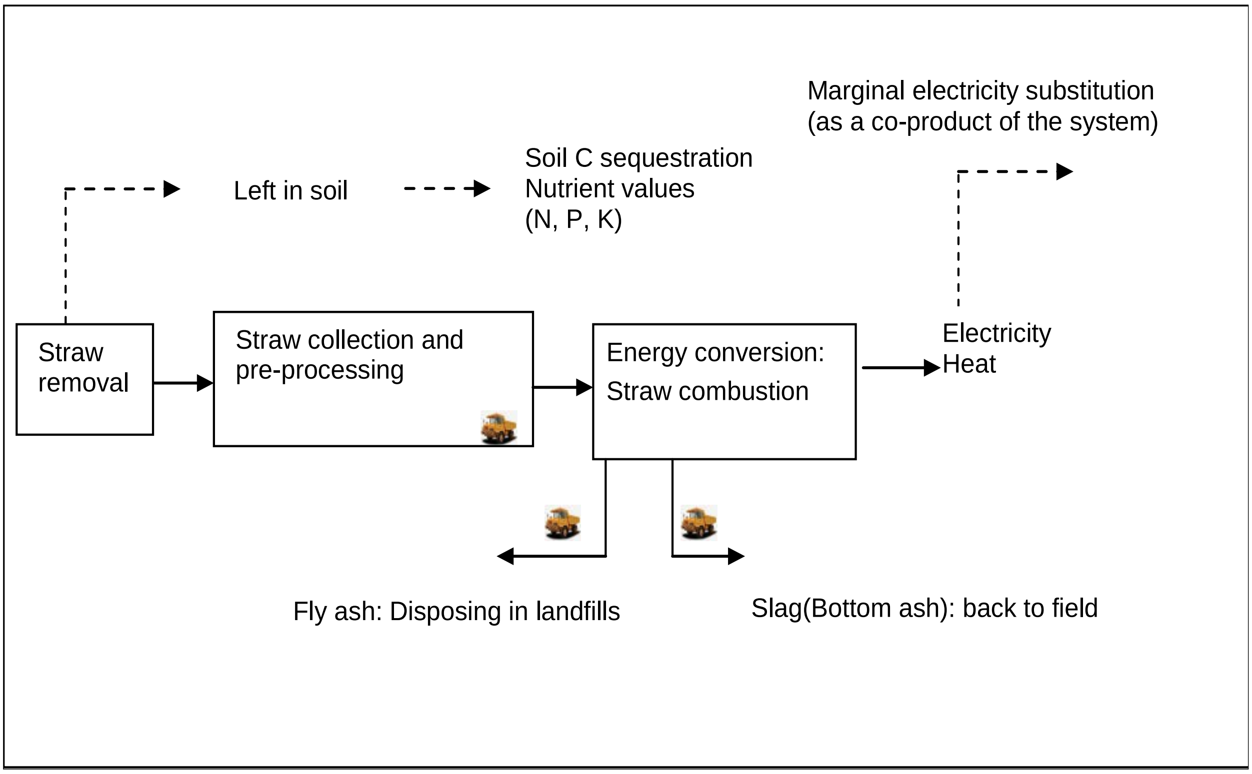

Figure 10: System boundary of the reference flow of Wheat straw

The system boundary is comprised with key processes, starting from the straw removal, collection and pre-processing (including field transportation), delivery of dry matter (DM) for the energy production (transportation), combustion of DM, and management of fly ash and bottom ash (slag).

The functional unit for the LCA is 1 MJ of heat produced from the reference flow of DM. The ‘reference flow’ refers 1 t of straw (with 85% DM) to produce the equivalent amount of heat from the CHP. The environmental performance of the heat production is finally estimated per 1 MJ of heat (functional unit).

3.3. Process Description and Assumptions

3.3.1. Straw removal

Impacts of straw removal are primarily associated with the perspectives, including reduction in the soil fertility, and nitrate leaching (Cherubini and Strømman 2011). It is also found that, if straw has to be removed from the field for other purposes, such as fuel, an equivalent amount of fertilisers should be added to compensate the nutrient value, which would have been available from the straw if ploughed back to the field (Nguyen et al. 2013).

Life Cycle Inventory (LCI) (Table 5), thus firstly deals with the estimation of the avoided soil C sequestration potential, and quantity of fertiliers to be added to compensate the nutrient removed followed with the estimation of emissions associated with them. The total C in the straw is calculated based on the elemental composition of straw as reported in Møller et al. (2005) (see section 2.3). The soil C sequestration potential from the residues is estimated based on the assumption that 88 kg C (i.e. 8.8%) of the total C content in the crop residues is retained by the soil in the time frame of 100 years (Petersen et al. ; Petersen and Knudsen 2010).

Mass of inorganic fertilisers required to compensate the Nitrogen (N), Phosporous (P) and Potassium (K) are estimated based on the elemental composition of straw. In addition to this, while estimating the fertiliser N value of the residues, 30% of the N in straw is assumed to be available as nutrients (Petersen and Knudsen 2010). P and K fertiliser values are estimated with an assumption that 100% of the nutrients values are available as fertiliser. Similar assumption for estimating nutrients available as (P and K) from the residues is found in the study such as Nguyen et al. (2013). The P and K values are further transformed to P_2O_5 and K_2O, by factoring with the ratio of their molecular weight, while modeling the LCA. Emissions from the compensated fertilisers and effects due to straw removal (leaching) are calculated as follows;

N_2O-N (direct):

Emissions from fertilizer inputs is estimated using the equation 1, based on the IPCC guideline (IPCC 2006).

$$N_2O\text{-}N_{direct,t} = N_2O\text{-}N_{N\ (inputs)} + N_2O\text{-}N_{(residues)}$$

Equation1

Where,

$N_2O_{direct\text{-}N,t}$= Direct N_2O emission as a result of nitrogen application within the project boundary, t-CO_2-e in year t

$N_2O\text{-}N_{N\ (inputs)}$ = N_2O-N from additional fertiliser (N) application = EF1*FSN

$N_2O\text{-}N_{(residues)}$ = N_2O-N emissions from the residues = EF_1*kg of N in crop residues

F_{SN} = annual amount of synthetic fertliliser N applied to soils, kg N y^{-1}

EF_1 = Emission Factor for emissions from N inputs, tonne-N_2O-N (t-N input)$^{-1}$ = 0.01 per kg of N input

N_2O-N (indirect)

N_2O-N (indirect) is calculated from the N volatilised and leached from the field. According to IPCC (2006), the indirect N_2O-N can be calculated as

$$N_2O\text{-}N_{indirect\text{-}N,t} = Frac_{leach}{*}NO_3\text{-}N{+}Frac_{gasf}{*}(NH3\text{-}N{+}NOx\text{-}N)$$

Equation2

where:

$Frac_{gasf}$ = fraction of synthetic fertliliser N that volatilises as NH_3 and NOx, kg N volatilised (kg of N applied)$^{-1}$ =0. 1* kg of N in fertiliser.

$Frac_{leach}$ = fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N additions)$^{-1}$ = 0.3 (see Table 11.3 of the IPCC guideline (IPCC 2006)).

NO_3-N is calculated from the amount of N in added fertiliser (F_{SN}), estimated according to (IPCC 2006), based on $Frac_{leach}$ which specifies the proportion of the N added to soils that is lost through leaching and runoff (see equation 3).

$$NO_3\text{-}N = Frac_{leach} * F_{SN}$$

Equation3

In addition to this the NO_3-N leading to leaching is estimated considering the below mentioned approach;

NO_3-N from additional fertiliser (potential changes in the leaching due to straw removal) = (N application due to additional fertiliser –N output in straw removed-N emissions from additional N fertilizer-(-N_2O-N from crop residues-N build up in soil) (Nguyen et al. 2013). N-build up in the soil is estimated considering the 100-years soil C sequestration potential and the C/N ratio of 1:10. Detail calculation steps to estimate these emissions are highlighted in section 3.5 of this thesis (Table-5).

The sum of nitrogen in ammonia and nitrogen oxides (NH_3-N + NO_X-N) is also calculated according to (IPCC 2006), based on $Frac_{gasf}$, which specify the proportion of the N in synthetic fertiliser (F_{SN}) that is volatilised as ammonia and NO_X (equation 4).

$$(NH_3\text{-}N + NOx\text{-}N) = F_{SN} * Frac_{gasf} * EF_4$$

Equation4

EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, [kg N–N_2O (kg NH_3–N + NOx–N volatilised)$^{-1}$] = 0.01

EF_5 = emission factor for N_2O emissions from N leaching and runoff, kg N_2O–N (kg N leached and runoff)$^{-1}$ =0.0075

The total amount of respective Nitrogen-ions, as stated in above equations are accounted in the model after estimating their mass, based on the molar weight of the respective compounds. For e.g. for N_2O, mass of N_2O-N is factorized with the molar weight (44/28).

With the above mentioned methodologies, the LCI for the 'straw removal process' are developed, which is shown in section 3.5 (Table 5)

3.3.2. Collection and Pre-processing

This process describes about the supply chain of the biomass, where collection, pre-processing and transportation of the biomass are accounted. The pre-processing includes the consumption of fossil fuel in the processing of straw; including baling and handling in the field (see LCI, Table 6).

3.3.3. Combustion

The thermal and electrical efficiency of a CHP (straw fired) considered in the study are 60% and 25% respectively (www.videncenter.dk 2004; energinet.dk 2012). The study has also assumed that heat is the main product of the system and the electricity generated is the co-product. In one of the study of similar kind, such as Rasburskis et al. (2006), heat is considered as the main product, whilst, Vikman et al. (2004) simultaneously considered both heat and electricity as the main product. Furthermore, in many Northern and Western European countries including Denmark, the electricity is sold as additional product (Lund and Andersen 2005; Rasburskis et al. 2006). In addition to this, from the trend of heat and electricity production from the CHP installed in Denmark, it is found that the former covers the higher shares than the latter. For .e.g. in 2011 the share of CHP in the gross district heat production was 76%, where the electricity share of this thermal production was 63% (see Figure 4, section 2.4.2). The co-produced electricity is further treated as an avoided product (refer glossary), since the simultaneous production of electricity displaces/avoids the additional production of electricity in the total electricity mix and consequently displaces the environmental impacts associated with them.

Nielsen (2004) reported that 40 MJ of heat and 110 kWh of electricity per t of straw (85% DM) is required in the combustion process. It is assumed that both heat and electricity required for the combustion are from the produced power anticipated in the system boundary. Thus, of the gross heat (refer glossary) produced from 1t (85% DM) of straw (i.e. 10440 MJ), the estimated net heat (refer glossary) is 10400 MJ. In the same manner, the net electricity production is estimated (Table 6). The net fuel required is thus re-estimated considering the net heat output of the system. Emissions from the combustion of the feedstock is based on (Nielsen 2004) (see section 3.5., Table 6). Despite there are other direct emissions, but considering the scope and impact categories selected for this study they are not taken into account.

3.3.4. Slag and Fly ash management

The total ash is estimated assuming that average amount of ash production is 6.3% per tDM of the winter wheat (ECN 2009). Slag from the combustion of wheat straw is found to be 54 kgtDM-1 (Nielsen 2004), which is 86% of the total ash. Fertiliser values (P_2O5 and K_2O) of the slag, are estimated considering the P and K content of the ash, which are 2.8% and 22.4% respectively (ECN 2009). 100 % of the nutrient values present in the bottom ash is assumed to be collected (Nguyen et al. 2013). Nutrient values of the slag return to farmland are also regarded as ‘avoided product’. Similarly, fly ash (deposit) is assumed to be 8.3 kg per tDM (Nielsen 2004), which is 14% of the total ash produced from the combustion of DM. Transportation distance of slag is considered similar to that of the distance of transporting the dried biomass (i.e. 200 km).

3.4. Scenario Development

Scenarios are developed on the basis of the objectives of the study, where the principal aim is to assess the environmental impacts of utilising wheat straw in a cogeneration unit, and secondary objectives for assessing the environmental consequences, if alternatively NG and Wood pellets are fired. Furthermore, the alternative scenarios are developed considering their stake in the fuel types and their consumption in the gross district heat production in Denmark. The Danish energy statistics shows that in the year 2011, of the total district heat production (132 PJ), NG had the share of 26%, making them among the principal fuel source in the production. Whilst, biomass had the total share of 37% of the total district heat production. On the gross district heat production, wood fuel had a share of 19%, followed by waste 10%, straw 7%, and bio-oil less than 1% (Danish Energy Agency 2011). Möller (2003) reported that due to scattered and heterogeneous forest, forest based biomass supply chain is cost intensive, and has been one of the reasons that have compelled Denmark to increase the import amount of fuel woods from the Baltic region. Hence, it could be interesting to compare the domestically produced biomass (such as straw) and imported biomass (such as wood pellets). In addition to this, as discussed in section 2.4.3, there are different perceptions on the marginal electricity production, primarily guided from the country specific energy polices, long term energy plans and renewable energy strategies, environmental regulations, and cost. Based on these perceptions Coal, NG and Wind power are assumed as marginal production in this thesis, which are integrated with the fuel scenarios (Table 4).

Table4: Matrix of district heat production scenarios

Fuel Scenarios	Fuel+marginal electricity scenarios		
	Marginal electricity (ME) substitution		
	NG	Coal	Wind Power
Combustion of Wheat Straw scenario (CoWS)	$\mathrm{CoWS}_{\mathrm{me1}}$	$\mathrm{CoWS}_{\mathrm{me2}}$	$\mathrm{CoWS}_{\mathrm{me3}}$
Combustion of Natural Gas scenario (CoNG)	$\mathrm{CoNG}_{\mathrm{me1}}$	$\mathrm{CoNG}_{\mathrm{me2}}$	$\mathrm{CoNG}_{\mathrm{me3}}$
Combustion of Wood pellets scenario (CoWP)	$\mathrm{CoWP}_{\mathrm{me1}}$	$\mathrm{CoWP}_{\mathrm{me2}}$	$\mathrm{CoWP}_{\mathrm{me3}}$

3.5. Life Cycle Inventory

LCI for CoWS are developed on the basis of processes as depicted in the system boundary, whilst for CoNG it is based on the database of the Ecoinvent Centre (2010), and for Wood pellets it is based on the study Schmidt and Brandao (2013)

3.5.1. Straw as Fuel input

LCI for wheat straw utilisation has covered the key process of energy conversion as shown in the System Boundary (Figure 10). Table 5 shows the LCI of the straw removal. Table 6 shows the LCI for the two processes: (1) collection and pre-processing (2) combustion including management of fly ash and bottom ash (slag). Methodology adopted for estimating the materials inputs and corresponding output of the system are discussed in the section 3.3, and shown in Table 5 and 6 of this section. Assumptions for the estimation are further elaborated at the bottom of the respective tables.

Table 5: LCI of straw removal

	Unit	Amount	Comments
100-years Soil C sequestration potential loss (kg CO_2-eq)	Kg	141	Estimated from the Carbon content[1]. 8.8% of C content in the straw (100 years)[2]
Additional Fertiliser inputs (compensation of nutrients)			
N	kg	1.53	Assumed as Calcium Ammonium Nitrate. N = 30% *kg of N in 1 t straw (85%DM)[3]
P	kg	0.765	Assumed as Triple superphosphate (P_2O_5) P= 100%* kg of P in 1 t straw (85% DM)[4]
K	kg	12.75	Assumed as Potassium Chloride (K_2O) K = 100% * kg of K in 1 t straw (85% DM)[5]
Emissions			
N_2O-N from extra N application as a fertilizer	Kg	0.0153	0.01* kg N in fertiliser. (Equation 1)
Avoided N_2O-N from crop residues	Kg	- 0.051	0.01*kg N in crop residues[3]. (Equation 1)
NH_3-N from added fertiliser-N application	Kg	0.0306	0.02*kg N in fertiliser (Nemecek and Kägi 2007)
NO-N from additional fertiliser-N application	Kg	0.0107	0.007*kg N in fertiliser (Nguyen et al. 2010)
N_2-N from additional fertiliser-N application	Kg	0.0719	0.047*kg N in fertiliser (Nguyen et al. 2010)

NO_3-N from additional fertiliser (potential changes in the leaching due to straw removal) [6]	kg	-0.0609	Estimated considering the changes in the leaching due to straw removal (Equation 3 and Nguyen et al. (2010)
Indirect N_2O-N[7]	kg	0.032	0.0075*NO_2-N+0.01*(NH_3-N+NOx-N) (Equation 2 and Equation 4)

Assumptions:

[1] [Composition of straw (85% DM); C=47.3%, N=0.6%, P=0.09%, K=1.5%] (Møller et al. 2005)

[2] Soil C sequestration= C content in straw*0.85*8.8% = 47.3%*1 t*0.85*8.8%.

[3] kg of N in the crop residues (1 t straw, 85% DM) = (0.6%*1 t straw*0.85) = 5.1 kg. (see section 3.3.1)

[4] kg of P in the crop residue (1 t straw, 85% DM) =0.09%*1 t straw*0.85 = 0.765 kg (see section 3.3.1)

[5] Kg of K in 1 t of straw (85% DM) = 1.5%*1 (kg)*0.85*100%

[6] NO_3-N (from additional fertiliser) = (N application due to additional fertiliser –N output in straw removed-N emissions from additional N fertilizer-(-N_2O-N from crop residues-N build up in soil) = 1.53-5.1 - 0.0719 - (-0.051-3.53) = -0.0609. See section 3.3.1.

[7] Indirect N_2O-N = 0.0075*4.3+0.01*(0.0306+0.0107)

Table 6: LCI of district heat production based on straw fired CHP plant

Process	Unit	Amount	Comments/Remarks	LCI data
Collection and pre-processing				
Inputs				
Amount of straw	t	1		
Baling and Handling[1]	MJ	61	2 lt^{-1} of fresh biomass	
Chopping straw at power plant[2]	MJ	6.46	0.18 $ltDM^{-1}$	
Transport (to power plant)	tkm	170	0.85 tDM * 200km (Lorry (>32 t)	(Ecoinvent Centre 2010)
Outputs	t	1	1 t (85% DM) at Power plant	
Combustion (1 t, 85% DM)				
Inputs				
Straw, 85% DM	t	1	LHV=14.5 GJ/t	
Heat (own product)[3]	MJ	40	per tDM	
Electricity (own product)[3]	kWh	110	per tDM	
Outputs (CHP)				
Heat	MJ	8700	Net heat[3] = gross heat output-heat input	
Net heat output	MJ	8660		
Electricity	kWh	1006	Net electricity[3] = gross electricity output-electricity input	
Net electricity output	kWh	897		
Bottom ash (slag) recycling[4]	Kg	54		
Transport to proper sites, by truck	tkm	10.8	Lorry (>16 ton) for 200 km	(Ecoinvent Centre 2010)
Nutrient[5]	kg			(Ecoinvent Centre 2010)
P fertilizer value		0.783	Fertiliser value	
K fertilizer value		8.64	Fertiliser value	
Fly ash disposal in landfills	kg	8.3	Fly ash deposits per tDM (Nielsen 2004)	(Ecoinvent Centre 2010)
Related emissions	g		*Direct emissions from fuel input[6]*	
CH_4		7.25		
N_2O		20		
SO_2		680		
NOx		1900		
HCl		670		

Assumptions:

[1] Estimated diesel consumption for baling, and handling per tDM based on Dalgaard et al. (2001). LHV of diesel =35.9 MJl^{-1}.

[2] Estimated diesel consumption for chopping 1 t of straw based on Nielsen (2004).

[3] Heat and electricity required during combustion process per tDM (Nielsen 2004).

[4] Total ash =6.3% per tDM=63 kg Slag from 1 tDM of wheat straw =86% of total ash= 54 kg (Nielsen 2004)

[5] Nutrient Value =Total bottom ash* P and K content in the ash. [Nutrient (P) =54*1.45%; Nutrient (K) = 54* 16%. Average wt of P and K content in the total bottom ash are 1.45% and 16 % based on videncenter.dk (1998).

[6] database for emissions from the combustion of wheat straw based on Nielsen and Illerup (2003) and Nielsen (2004). (See Appendix 3)

The product networks considered in the modeling of life cycle processes of CoWS$_{me1}$ is shown in Appendix 4 and 5.

3.5.2. NG as Fuel input

LCI for the NG as a fuel input are based on the database of Ecoinvent Centre (2010), which covers the primary processes such as extraction, transportation and combustion of the fuel. To make the assessment comparable with the straw fired CHP plant, fuel value of NG (in MJ) required to produce the equivalent district heat (8660 MJ) is estimated. Thermal and electrical efficiency of CHP are assumed to be same as described for the straw fired CHP plant (see section 3.3.3). The process flow diagram for NG based district heat production is shown in Appendix 6.

3.5.3. Wood Pellets as Fuel input

It is assumed that 100% of the wood pellets (Pine based) are imported from Latvian natural forest, and The LCI for the energy conversion process of wood pellets is based on the study carried out by Schmidt and Brandao (2013). The methods for developing the LCI of the pellets starts from calculating the quantity of pellets required (in terms of physical weight, tDM and its energy values) for producing equivalent amount of net heat produced from the straw fired CHP plants (i.e. 8660 MJ, see Table 6). The reason behind adopting this idea is to make the assessment comparable with the common functional unit. Furthermore, the energy content of pellets and straw are different, and to produce the same amount of district heat, total DM of pellets is required to be estimated, which represents the common reference values. The thermal and electrical efficiency of the combustion system are assumed to be similar to the straw fired CHP plant (see section 3.3.3).

Schmidt and Brandao (2013) reported about the CO_2 emissions from the residue decay and potential uptake of CO_2 from the biomass growth (such as Pine in Latvia). Wood pellets based on Pine and harvested in Latvia, is found emitting 112.7 kg CO_2 per tDM because of the residue decay, which is assumed to be avoided if used as energy fuel. Similarly, CO_2–uptake per tDM is estimated to be 1411.97 kg, which is based on (Schmidt and Brandao 2013). This estimated amount of carbon sequestration is thus avoided if the biomass is harvested for pelletisation. Hence, the emission from the residue decay is subtracted and the potential carbon sequestration are added while developing the LCI for the estimated quantity of the pellets required for producing the equivalent amount of district heat (Table 7).

Table 8 describes about the LCI of two processes (1) collection and pre-processing (2) combustion including management of flyash and slag. The LCI is formulated based on database presented in Schmidt and Brandao (2013). Before the delivery of the DM, the wood pellet are assumed to be collected and pre-procesed in Latvia. The collection and pre-processing involves the process of drying and pelletisation. Drying of the biomass includes the production of the biomass with about 10% moisture content, suitable for combustion process. Schmidt and Brandao (2013) reported that 1 kg of wood pellet contain 0.1 kg of water, which indicates that to produce 0.9 kg (90% DM) of pellets, 1 kg of fresh biomass is required. Fuel used for the drying process is assumed to be wood pellets, and mechanical energy required for pelletisation (i.e. diesel consumption) is estimated based on the study Schmidt and Brandao (2013). Magelli et al. (2009) have reported that drying and pelletisation of wood residues is one of the major energy consuming processs in the energy conversion chain of pellets. But drying and pelletisation are also integral process for increasing wood densification, to transform the bulky wood residues into a more useful and clean energy resources, and also to ease in transportation for a long distance.

The processed biomass (with 90% DM) are assumed to transported through freight ships from Latvia to Denmark, and then further transported locally to the power sites. The distance of the transportation for the former is assumed to be 845 km and for the latter is 200 km (Schmidt and Brandao 2013). The combustion process (assumed to be with similar thermal and electrical efficiency of straw fired CHP), is expected to produce 8660 MJ of net heat, and the required DM of pellets are 0.824 t. This quantity of DM is collected, pre-processed and transported to the power plants, as described above. The total ash is estimated as 0.5% per tDM of wood pellets (ECN 2009). The proportion of slag and fly ash is assumed similar to the wheat straw. Nielsen (2004) reported that for straw the slag and fly ash are 54 $kgtDM^{-1}$ and 8.3 $kgtDM^{-1}$ respectively, which is 86% and 14 % respectively of the total ash of the straw (i.e.

63 kg) (see section 3.3.4). Slag and fly ash from the combustion of pellets are estimated based on these assumptions.

Table 7: LCI of Forest residues removal (Pine, Latvia)

Parameters	Unit	Amount	Comments
Reference flow	t	0.824	Estimated quantity of pellets required to produce the equivalent amount of heat as estimated for straw fired plant[1]. 0.91 t of fresh biomass required to produce 0.824 tDM (with 90% DM).
Soil C sequestration loss, 100 years perspectives. (Kg CO_2-eq)	kg	1163	Estimated from the CO_2- uptake per 0.824 tDM[2].
CO_2-emission from residue decay, 100 years perspectives (Kg CO_2-eq)	kg	-93	Estimated from the decay of residue, originated for the reference flow of pellet[3].

Assumptions:

[1] Fresh biomass (1 kg of fresh biomass = 0.9 kg DM). Amount of wood pellets estimated considering the net heat output calculated for straw (8660 MJ). LHV of wood pellet =17.5 $MJkg^{-1}$ (Schmidt and Brandao 2013). The total energy content of Pellet required for producing equivalent district heat = 14420 MJ.

[2] CO_2-uptake per tDM estimated as 1411.97 kg CO_2 (Schmidt and Brandao 2013).

[3] CO_2 emission from the residue decay 1tDM =112.7 kg CO2, based on (Schmidt and Brandao 2013).

The fertiliser value of the slag are estimated based on the proportion of P and K content in the slag produced from the straw combustion, as reported in videncenter.dk (1998), where the average proportion of the former is reported to be 1.45% and the latter is 16% of the total slag produced. Slag and fly ash are managed by transporting the former to the agriculture field (as nutrients) and the latter is disposed in a land fill. The product networks considered in the modeling of life cycle processes in the chain of Wood pellet conversion to district heat production is shown in Appendix 7 and 8.

Table 8: LCI of district heat production fired with Wood pellets in a CHP plant, reference flow 0.824 tDM

Process	Unit	Amount	Comments/Remarks	LCI data
Collection and pre-processing				
Inputs				
Amount of Wood Pellets	t	0.91	Fresh biomass[1] (Table 7)	
Fuel for mechanical energy	MJ	208	Production of pellets at Latvia[2]	(Ecoinvent Centre 2010).
Heat, (drying of wood pellets)	MJ	2780	Production of pellets at Latvia[3]	(Ecoinvent Centre 2010).
Electricity, (drying of wood pellets)	MJ	435	Electricity, medium voltage, Chez Republic Mix[4] (Appendix 2)	(Ecoinvent Centre 2010).
Transport (freight ship from Latvia)	tkm	696	Transport of pellets from Latvia to Denmark (845 km) [5] (Schmidt and Brandao 2013)	(Ecoinvent Centre 2010).
Transport (to power plant)[b]	tkm	165	Transport to power plant within Denmark (200 km) [6] (Lorry (16-32 t)	Lorry, 16-32t, EURO5/RER (Ecoinvent Centre 2010).
Outputs	t	0.824	Reference flow of feedstock available at Power plant*	
Combustion				
Inputs				
Wood Pellets, 90% DM	t	0.824	LHV=17.5 MJ/kg	
Outputs (CHP)				
Net heat output	MJ	8660	Net heat = gross heat –heat input	
Net electricity output	kWh	897	Net electricity = gross electricity output-electricity input	
Bottom ash (slag) recycling	Kg	3.54	Based on slag content of straw[7]	
Transport to proper sites, by truck	tkm	0.708	Lorry (>16 ton) for 200 km	(Ecoinvent Centre 2010).
Nutrient[8]	kg			(Ecoinvent Centre 2010).
P fertilizer value		0.051	Fertiliser value	
K fertilizer value		0.56	Fertiliser value	
Fly ash disposal in landfills	Kg	0.57	Fly ash deposits per tDM[9]	(Ecoinvent Centre 2010).

Related emissions	g		*Direct emissions from the fuel input)* [10]
CH_4		30.28	
N_2O		11.53	
SO_2		25.95	
NOx		995	
HCl		12.97	

* the reference flow is equivalent to 10400 MJ of fuel input

Assumptions:

[1] estimated quantity of Pellets to produce 8660 MJ of district heat from CHP plant (see Table 7).

[2] Diesel, burned in building machine/GLO (Ecoinvent Centre 2010). Diesel consumption for mechanical energy =0.206 MJ per 0.9 kg DM (Schmidt and Brandao 2013).

[3] Wood pellets as a fuel for drying and burned in a furnace in Latvia. 2.75 MJ of heat required for drying of pellets to 10% moisture content , resulting to produce 0.9 kg DM (Schmidt and Brandao 2013).

[4] electricity required for drying the wood pellets to produce 0.9 kgDM at Latvia. 0.43 MJ of electricity per 0.9 kgDM of pellets (Schmidt and Brandao 2013)

[5] transport, freight ship for pellets from Latvia to Denmark requiring 0.0483 tkm per 1 MJ of energy content of pellets (Schmidt and Brandao 2013)

[6] transport, lorry, within Denmark to deliver in the power plant, requiring 0.0114 tkm of energy per 1 MJ of heat content of pellets (Schmidt and Brandao 2013)

[7] 86% of the total ash assumed as bottom ash. Total ash content of pellets= 0.5%tDM^{-1} (ECN 2009). Total ash =0.5%*0.825tDM = 4.12 kg. Bottom ash = 86%*4.12 kg =3.54 kg

[8] P and K value assumed to be same of ash of straw. Nutrient Value =Total bottom ash* P and K content in the ash. [Nutrient (P) =3.54*1.45%; Nutrient (K) = 3.54* 16%. Average w.t. of P and K content in the total bottom ash are 1.45% and 16 % based on videncenter.dk (1998)

[9] 14% of the total ash assumed for fly ash. Fly ash =0.14*4.12 kg

[10] emissions database based on combustion of wood reported in Nielsen and Illerup (2003). See Appendix 3.

3.5.4. LCI for marginal electricity substitution

The LCI for the marginal electricity technology are based on the sources as shown in Table 9.

Table 9: Marginal electricity production and sources of respective LCI

Sub-scenarios	LCI database and source	Retrieved from
NG	'Electricity NG' (LCA Food DK)	SimapRo.7.3.1.
Coal	'Electricity, hard coal, at power plant/DE U' (Ecoinvent Centre 2010)	SimapRo.7.3.1.
Wind Power	'Electricity, at wind power plant/RER U' (Ecoinvent Centre 2010)	SimapRo.7.3.1.

3.6. Tools, LCA Method, Impact categories and Approach

The "SimaPRO 7.3.3" (PRé Consultants 2012) is used as an LCA tool. The "Stepwise2006"method (2.0 LCA consultant 2012) is used for the impact assessment. Environmental performances in relation to the functional unit are assessed in terms of impact categories as described in section 3.1. GWP factors of methane (CH_4), and di-nitrogen monoxide (N_2O) found in the 'Stepwise 2006 method' are adjusted to 25 and 298 respectively for 100-year time horizon, which are based on IPCC (2007). Eutrophication (aquatic) is assumed to be have impact on the lake, which is based on the study Yang et al. (2008), where it is reported that historically Danish lakes are regarded highly eutrophic.

Consequential LCA (CLCA) is considered instead of the 'Attributional LCA', because it allows to look into important aspects such as; the environmental differences between a 'product being at a place' or 'removed', and 'impact of replacing other products available in the market by co-products' (Schmidt 2008). CLCA attempt to model the LCA of resource utilisation, considering that marginal suppliers are affected and allocation of co-products are avoided through the expansion of the system (Schmidt 2008). The significance of this approach exists when we have to assess the changes in the environmental consequences due to changes in the demand of the marginal product (Dalgaard et al. 2008). For instance, in this study changes in the demand of electricity in the marginal electricity mix is reflected by the co-production of electricity, and reflects what will happen in the situation if the electricity is alternatively co-produced or not. The system is further expanded in forms of energy (electricity input) required during the energy conversion process, which is included while estimating the net heat production and quantity of the biomass required accordingly. Hence, in this study the CLCA approach allows to look into a potential changes in demand, since the co-produced electricity from the cogeneration unit is assumed to be utilised in the processing of biomass, and also the system is expanded by looking into effects of substituting marginal electricity and further displacing their associated environmental impacts of production.

3.7. Economic Evaluation

Economic evaluation of the district heat production is carried out for the scenarios CoWS, CoNG and CoWP. The evaluation parameters employed are NPV, EAC and LPC. To simplify the economic evaluation, an ideal CHP plant with 10 MW of thermal capacity is assumed. The production cost is further downscaled in relation to 1 MJ of district heat.

The NPV criteria (equation 5) facilitate to look the financial viability of the district heat production based on different fuel alternatives, and is important from the investors' perspectives (Lu et al. 2005; Parajuli et al. 2013).

$$NPV = \sum_{t=0}^{N} R_t * (1+i)^{-t}$$

Equation 5: NPV critera

Where,

NPV : Net Present Value

R_t : the total production cost in the year 't'

t : life time in years (0 or 1......n, assumed as 20 years)

i : Discount rate (assumed as 5%)

The EAC (equation 6-7) facilitates to estimate the total annual costs of power production compounding the investment and operation cost for producing district heat over its lifetime. This will help to compare technologies with different lifetimes or maturities of investments in different alternative scenarios (Economy Watch 2010; Parajuli et al. 2013).

$$EAC = NPV / (A_{t,i})$$

Equation 6: EAC critera

Where,

EAC : Equivalent annualised cost

At,i : Annuity factor

$$A_{t,i} = [1 - (1 + i)^{-t}] / i$$

Equation 7: Annuity factor

LPC (equation 8) facilitates to reflect the overall competitiveness of different investments, which also represents the present worth of the total cost of building and operating a power plant over an assumed financial life and duty cycle, converted to equal annual payments and expressed in terms of real price. It reflects overnight capital cost, fuel cost, fixed and variable operation and maintenance (O&M) cost for each technology (EIA 2011; Parajuli et al. 2013).

$$LPC = NPV * \sum_{t=0}^{N} Q_t /(1+i)^t$$

Equation 8: LPC

Where,

LPC : Levelised Production Cost

t : Years (0 or 1......n, assumed as 20 years)

Q_t : District heat Production in the year "t'

The capital cost, fixed and variable O&M cost are based on the estimates of Danish Energy Agency (energinet.dk 2012), and for the fuel cost, the projected fuel prices (including taxes and subsidies) (see Figure 7) as reported in Ea Energy Analyses (2010) are considered.

For NG, a combined cycle gas turbine (back pressure mode) is assumed and the investment cost per MW is 1.1 M€/MW, and the total O&M Cost is assumed as 2.5 €/MWh (energinet.dk 2012). For the straw fired CHP plant, the investment cost is assumed as 4 M€/MW, fixed O&M cost 40000 €/MW/year and variable O&M Cost 6.4 €/MWh (energinet.dk 2012). For Wood pellets, the investment cost is 2.6 M€/MW, fixed O&M cost 29000 €/MW/year and variable O&M Cost 3.9 €/MWh, which is considered similar to the back pressure mode operated wood chips fired CHP (energinet.dk 2012).

As discussed in the LCA process, about the displacement of environmental impacts of marginal electricity because of the co-produced electricity, in economic evaluation also from the gross LPC, the LPC of coal fired power is deducted. The gross LPC is calculated as per the equation 8. IEA and NEA (2010) have reported that for coal-fired power plants both with and without carbon capture, the levelised generation costs in OECD countries range between 54 USD/MWh (Australia) and 120 USD/MWh (Slovak Republic) at a 5% discount rate. In this thesis, it is assumed that if 1 MWh of coal based marginal electricity is displaced then it will displace 120 USD (equivalent to 92 €/MWh at the price of 2013-04-24). Hence, while estimating LPC/MWh, it is assumed that 0.415 MWh of the marginal electricity is displaced (0.415 MWh is produced electricity estimated with 1.66 MWh of fuel input while producing 1 MWh of heat with thermal efficiency of 60% and the electrical efficiency of 25%). It should be noted that in order to minimise the error in the economic evaluation, primarily because of the deviations in the fuel prices, the LPC is estimated by varying the fuel prices (see section 4.6).

3.8. Summary of Methodology

The overall approach of the study is shown in Figure 11. The LCA proceeds with the goal and scope definition, including selection of the functional unit (i.e. 1 MJ heat). Three scenarios are developed to represent the diversification of fuel types considered for producing district heat in a CHP, which are further integrated with sub scenarios representing the potential marginal electricity substitution because of the coproduction of the cogeneration unit. For all the fuel types, LCI are formulated on the basis of secondary databases. In the case of straw and pellets, effects of the biomass removal in the carbon sequestration are also analysed for the estimated mass of fuel inputs All the material and fuel inputs required in the energy conversion processes are modeled in the tool 'SimaPRO 7.3.3'. Modeling of the energy conversion processes are further accompanied by the evaluation of the environmental performances through the set of environmental impact categories, GWP, AP, aquatic and terrestrial EP, and NRE-use.

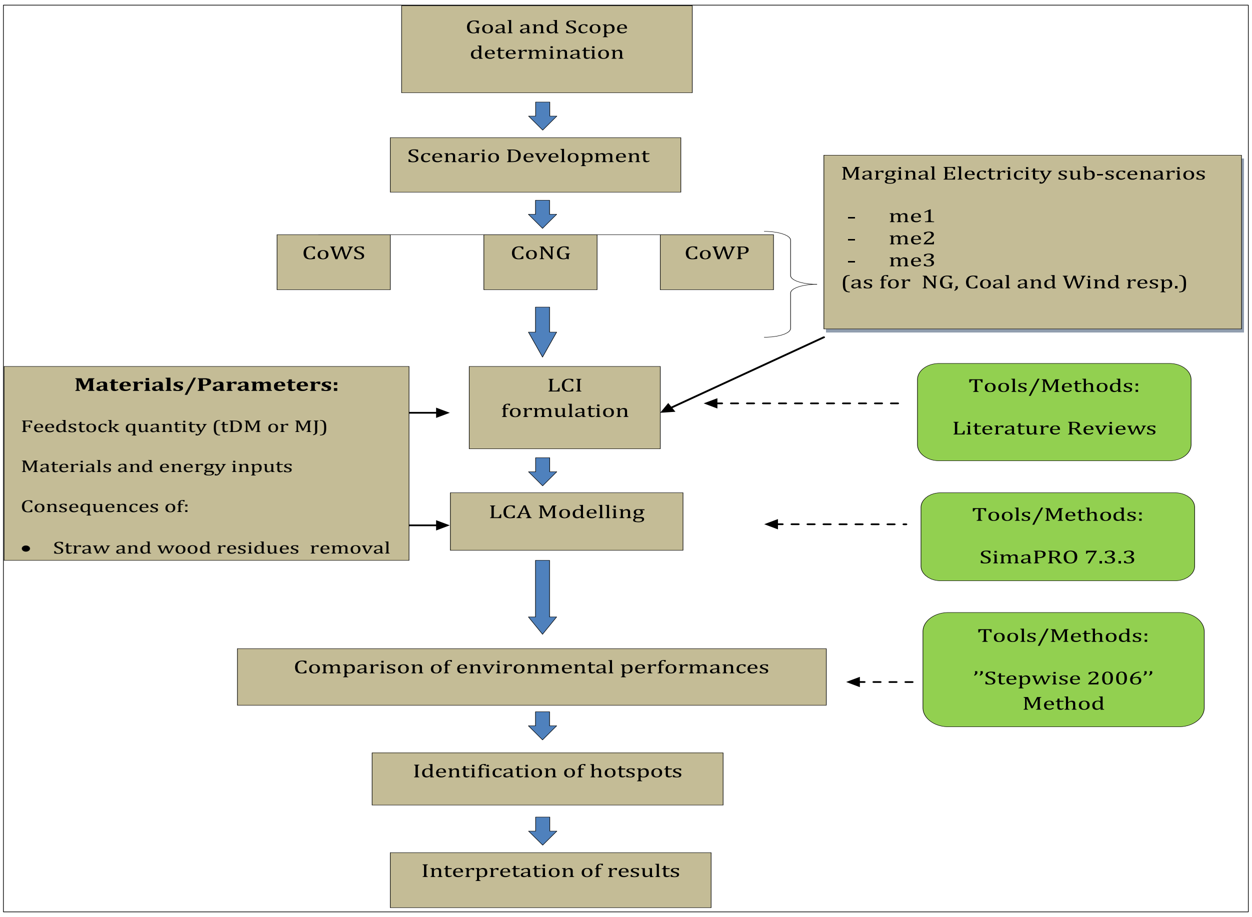

Figure 11: Overall Approach of the study (LCA perspectives)

The evaluation of the impact categories are carried out with the aid of LCA Method ‘Stepwise2006’. Hot spots (i.e. most influential process in relation to the environmental impact) in the energy conversion processes are also assessed in relation to the gross impact.

In order to come-up with a conclusion about the economic viability of different scenarios, a simple economic evaluation is carried out. NPV, EAC and LPC are the basis of economic evaluation to conclude from the perspectives of investors, annual cost of production and competitiveness of the fuel choices.

CHAPTER 4: RESULTS AND DISCUSSIONS

The environmental performances in the energy conversion processes for all the scenarios are presented and discussed in terms of gross and net impact. The gross impact refers to the positive (+) value in relation to the respective impact categories, whereas the net impact is defined as; the Gross impact minus the impacts that are assumed to be avoided (displaced) due to co-products of the system. For instance, displacement of NRE use in the production of chemical fertilisers, which is assumed to be possible with the recycling of nutrient values present in the bottom ash after applying in the agricultural field as a fertiliser.

Furthermore, before starting to discuss about the environmental performances in the life cycle processes of energy conversion in the three scenarios, it is necessary to estimate the environmental impacts associated with the marginal electricity substitutions. The reason behind this is that for all impact categories the net environmental impact are estimated from after potential displacement of the impacts associated with these marginal electricity production. Three different types of marginal electricity scenarios me1, me2, me3 have different level of environmental impacts, which indicates that, if any particular marginal technology has lower environmental impact, the net impact in the fuel scenarios will be higher. For instance, if GWP of wind power is lower than coal, then the net GWP of CoWS will be higher in the former marginal substitution compared to the latter one. After undergoing the LCA of the developed scenarios, economic viability of them are also tested.

4.1. Marginal electricity

The reference flow of the feedstock (1 t, 85% DM of the straw) is associated with the co-production of the net electricity, equivalent to 827 kWh (section 3.5, Table 6). This amount of electricity is assumed to be displaced from the marginal production. Three different types of marginal electricity scenarios are developed, which is aimed to investigate the significance of co-produced electricity in displacing the environmental impacts associated with the marginal production. This is useful in the context, where the Danish future electricity mix is expected to have more renewable including wind power, the displacement of which might sound environmentally inappropriate. This hypothesis shall be discussed in the assessment of environmental impact of the respective district heat production scenarios in the latter sections.

Figure 12 shows the life cycle impacts of producing 1 kWh of electricity from the selected marginal electricity technologies, where Wind Power is comparatively environmentally appropriate than the NG and Coal fired production. For e.g. the NG fired power plant leads to have GWP of 67.81 g CO_2-eq/KWh, and Coal and Wind power estimated to have 112.36 and 1.17 g CO_2- eq/kWh, respectively. In the same manner, acidification, eutrophication (aquatic and terrestrial), and NRE use is lower in the Wind power compared to other marginal technologies (Figure 12).

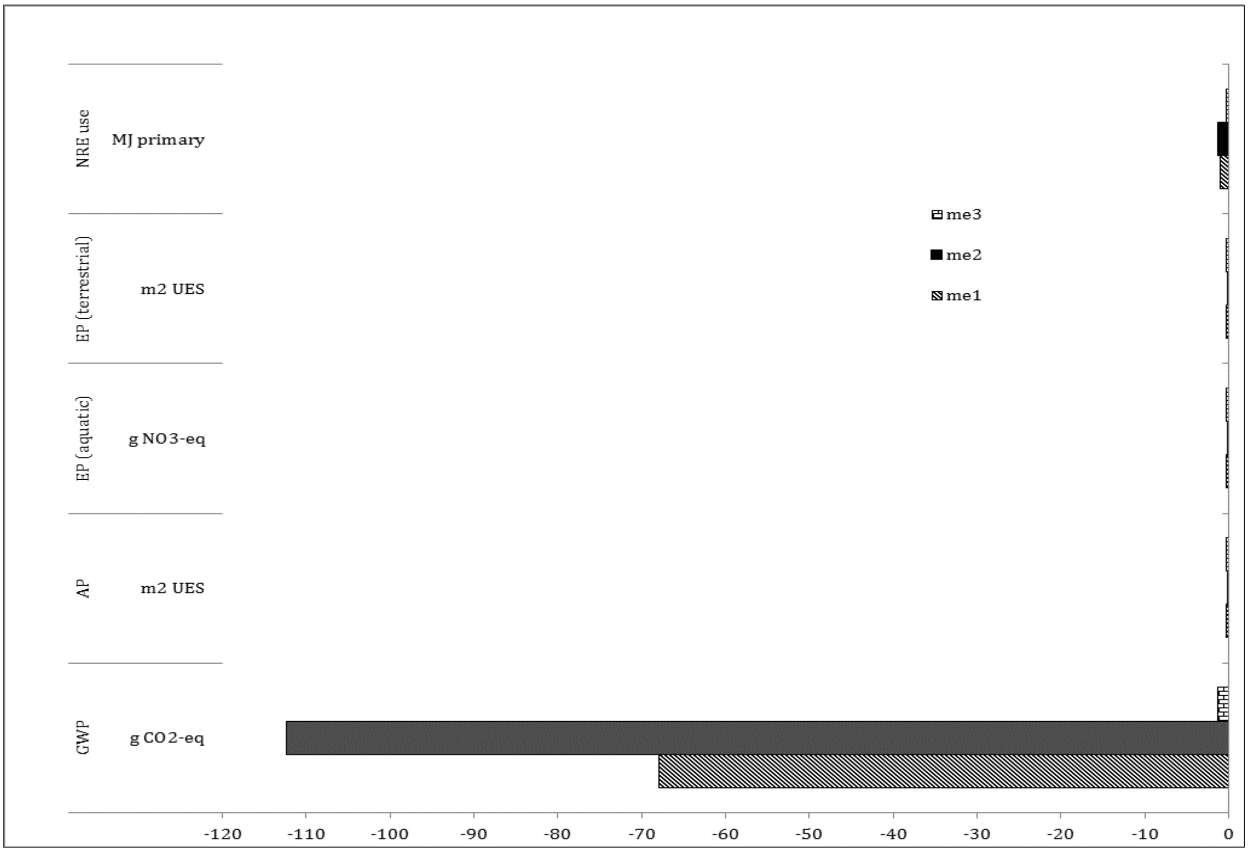

Figure 12: Life Cycle Impacts of producing 1 kWh of electricity from the selected marginal electricity producing units

This indicates that if electricity produced from Wind is eventually substituted by the co-produced electricity of the CHP plant, the environmental differences that can be achieved from the substitution of NG/coal by the biomass are insignificant, with less displacement of potential environmental impacts. For instance, if the electricity from the CHP displaces coal as the marginal electricity, then it will be able to reduce 112.36 g CO_2-eq for every 1 KWh of the displacement. Whilst if power produced from the system displaces the electricity generated from a Wind power, then will be able to reduce only 1.17 g CO_2-eq/kWh. The rate of reduction for other impact categories takes places accordingly as shown in Figure 12 for every unit displacement of electricity.

4.2. Consequences of straw removal

This is assessed by means of analysing the environmental impacts associated with the removal of the reference flow of the feedstock. The main consequence of the straw removal is about constraining the Soil C sequestration potential. Hence, this leads to have an effect in the GWP (CO_2eq), compared to the situation if the residue is not removed from the field. Another important consequence is about the environmental impacts associated with the application of compensating fertilisers, which would not have been required if the straw is remained in the field. Hence consequences of the removal of 1 t of the straw (85% DM) are primarily:

- 38.38 kg C, primarily as the soil C sequestration (100-years) potential is limited
- Compensation of fertilisers is required to fulfill the soil nutrients, which is removed with the straw. The compensation is estimated to be made from the addition of fertilisers with nutrient values equivalent to 1.53 kg. 0.765 kg, 12.75 kg (N, P, K).
- Emissions from the fertiliser applications (manufacturing) are the added impact associated with the compensating fertilisers.

In spite of above mentioned negative consequences, removal of 1 t (85% DM) of the straw contributes to potential avoidance of -0.051 kg N_2O-N leaching (as shown in LCI, Table 5).

The life cycle impact of above mentioned consequences are assessed in relation to the selected impact categories, which reveals that the removal process of 1 t of straw (85% DM) leads to increase the GWP by 135 kg CO_2-eq (Table 10). The tendency of limiting soil C sequestration due to the straw removal, including emissions of N_2O-N, NH_3-N, NO-N, as shown in Table 5, and further calculated in terms of CO_2-eq, contribute 87% of the total GWP (Table 10).

Table 10: Life cycle consequence of removal of 1 t (85% DM) of wheat as an energy carrier

Impact category	Unit	Total	straw removal (Soil C related)	Fertilisers compensation
GWP	kg CO_2-eq	135.49	118.14	17.34
AP	m^2 UES	2.84	1.14	1.70
EP, aquatic	kg NO_3-eq	0.78	-0.02	0.80
EP, terrestrial	m^2 UES	8.37	5.39	2.97
NRE Use	MJ-primary	185	0.00	185.16

Rest of the total GWP is due to emissions associated with the production of the estimated quantity of compensating fertilisers (Figure 13).

Apart from the GWP, other negative impacts to the ecology due to straw removal are contribution to the process of acidification because of direct emissions to air from the pollutants as described above and also from the manufacturing process of the compensating fertilisers. The straw removal process alone covers 40% of the total AP (2.84 m^2UES per 0.85 t straw) and the rest are due to the manufacturing process of the fertilisers.

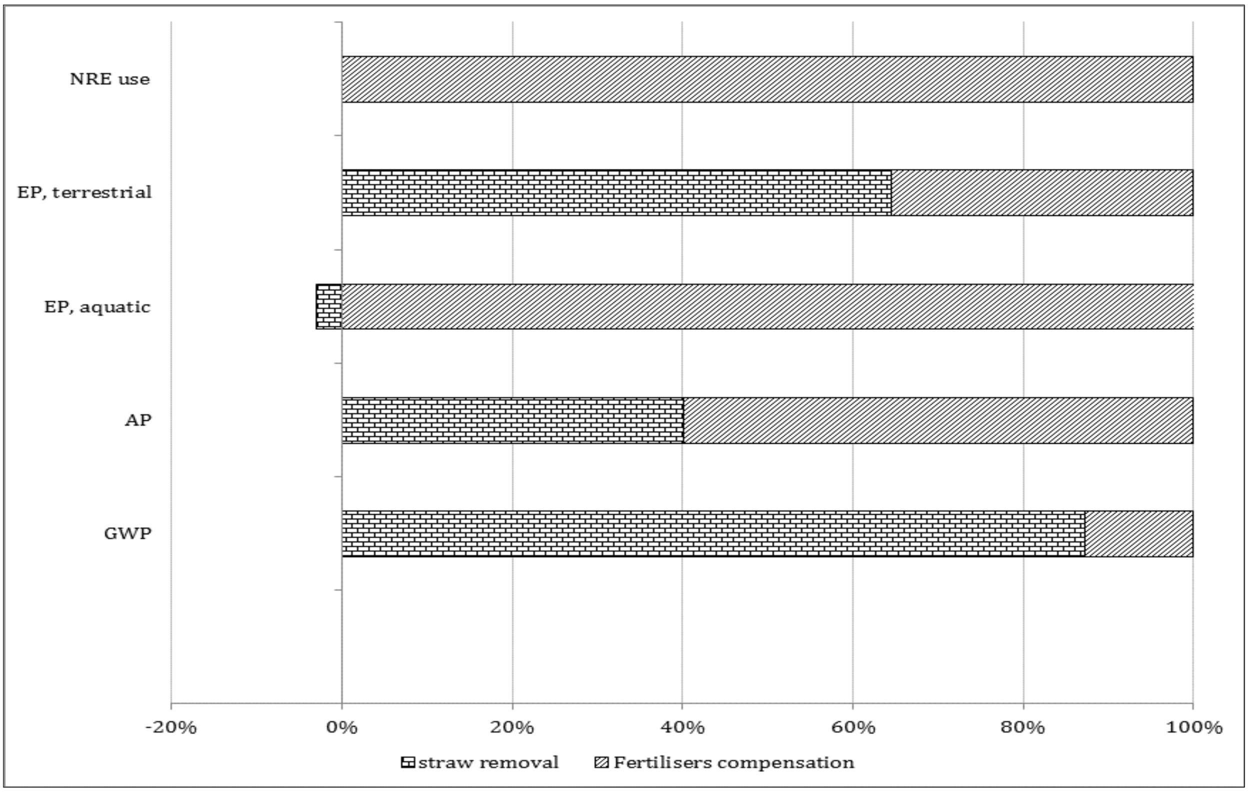

Figure 13: Environmental consequences of removal of 1 t (85% DM) of wheat straw

As the removal of straw is linked with the application of the fertilisers, this facilitates the leaching of nitrates to the water. Despite this, the same process also limits the tendency of soil-N buildup, which helps in reducing the total leaching potential compared to the situation of the biomass is not removed. As shown in the LCI (Table 5), potential changes in the leaching due to removal of the reference flow of the feedstock are -0.0609 kg NO_3-N, which accounts all the effects of nitrate leaching particularly from the fertiliser applications, emissions from the fertilisers applied to soil, N buildup in the soil, and emissions from the residue. The N-build up in the soil due to the crop residues is estimated from the 100-years Soil C sequestration potential and the C/N ratio (1:10), which results to 3.53 kg N per reference flow of the feedstock (Table 5). Hence, the straw removal process leads to have eutrophication (aquatic) potential as -0.02 per t straw (85% DM). Despite this the emissions to water from the production process of fertilisers leads to increase this potential by 0.8 kg NO_3-eq in every 0.85 t of the straw removal (Table 10). Of the total terrestrial eutrophication potential, emissions in regard to the straw removal process contribute 64% and the rest is covered by the manufacturing process of fertilisers. Likewise, energy inputs for the production of estimated quantity of fertilisers alone cover 100% of the total NRE use (185 MJ/1 t, 85% DM straw) (Figure 13).

In conjunction with the above mentioned consequences of the straw removal, the utilisation of the removed straw as a bioenergy source in the production of district heat is further discussed in section 4.3, which also assumes to displace NG fired district heat production. This indicates that the impacts associated with NG fired district heat production are displaced if straw is used as an alternative fuel.

4.3. Impact categories and Scenario evaluations

Environmental impacts of producing 1 MJ of heat in a CHP with three different fuels are discussed in relation to the selected impact categories. Since, the main aim of this study is to carry out the LCA of wheat straw as a fuel alternative to produce district heat, results and discussions are carried out in reference to the Scenario- CoWS. The life cycle impact of the energy conversions of the straw are assessed considering the reference flow of the feedstock, including the straw removal, collection and pre-processing, combustion and management of bottom ash and fly ash (see the system boundary, Figure 10). In the case of CoWP, the LCA of the energy conversions of wood pellets considers the processes: removal of wood residues from the natural forest of Latvia, transported to power plants in Denmark, combustion and finally management of fly ash and slag. Likewise, CoNG deals with the impact associated with the extraction, transportation, combustion, and management of waste. Environmental impacts are segregated into: 'Upstream' and the 'Downstream' process, the former involves processes starting from the removal of the biomass until delivery to the power plants and the latter involves the processes starting from the combustion to the management of the produced ash.

4.3.1. GWP

The gross GWP in the scenario CoNG with three marginal electricity scenarios is 102.18 g CO_2-eq/MJ heat. Similarly, the net GWP in $CoNG_{me1}$ is 39.66 g CO_2-eq/MJ heat (assuming NG fired electricity production as the marginal electricity). The displacement of GWP in relation to three marginal electricity scenarios occurs accordingly as discussed in section 4.1. For $CoNG_{me2}$ and $CoNG_{me3}$, the net GWP is estimated at -1.41 g CO2-eq and 101.11 g CO2-eq per MJ of heat production.

In relation to the scope of this study, the significance of producing the district heat in a CHP and also the recycling of the nutrient values available in the slag as a fertiliser are found rationally establishing their advantages. This aspect is well attributed when the displaced environmental impacts are considered. For e.g. the use of straw for every 1 MJ of district heat production leads to lower the GWP in a larger scale if coal fired power production (me2) is regarded as substitutable marginal electricity. The net GWP is estimated at -86.57 g CO_2-eq/MJ heat, despite the gross GWP is 25.86 g CO_2-eq/MJ heat. Likewise, in the case of $CoWS_{me1}$ and $CoWS_{me3}$, net GWP are -42 g CO_2-eq/MJ heat and 24.66 g CO_2-eq/ MJ heat, respectively.

In the case of $CoWP_{me1}$, $CoWP_{me2}$, $CoWP_{me3}$, net GWP per 1 MJ of heat production is 91.45, 47.3 and 158.49 g CO_2-eq respectively, even though displaces significant amount of the impact from the co-product, primarily electricity (Table 11 and Figure 14).

Table 11: GWP in the energy conversion process

	GWP (g CO_2-eq/MJ heat)								
	CoNG			CoWS			CoWP		
	me1	me2	me3	me1	me2	me3	me1	me2	me3
Upstream	8.28	8.28	8.28	24.89	24.89	24.89	158.76	159.16	159.16
Downstream	31.38	-9.69	92.82	-66.87	-111.42	-0.23	-67.31	-111.86	-0.67
Gross	102.18	102.18	102.18	25.86	25.86	25.86	159.26	159.66	159.66
Net Impact	39.66	-1.41	101.11	-41.99	-86.54	24.66	91.45	47.30	158.49

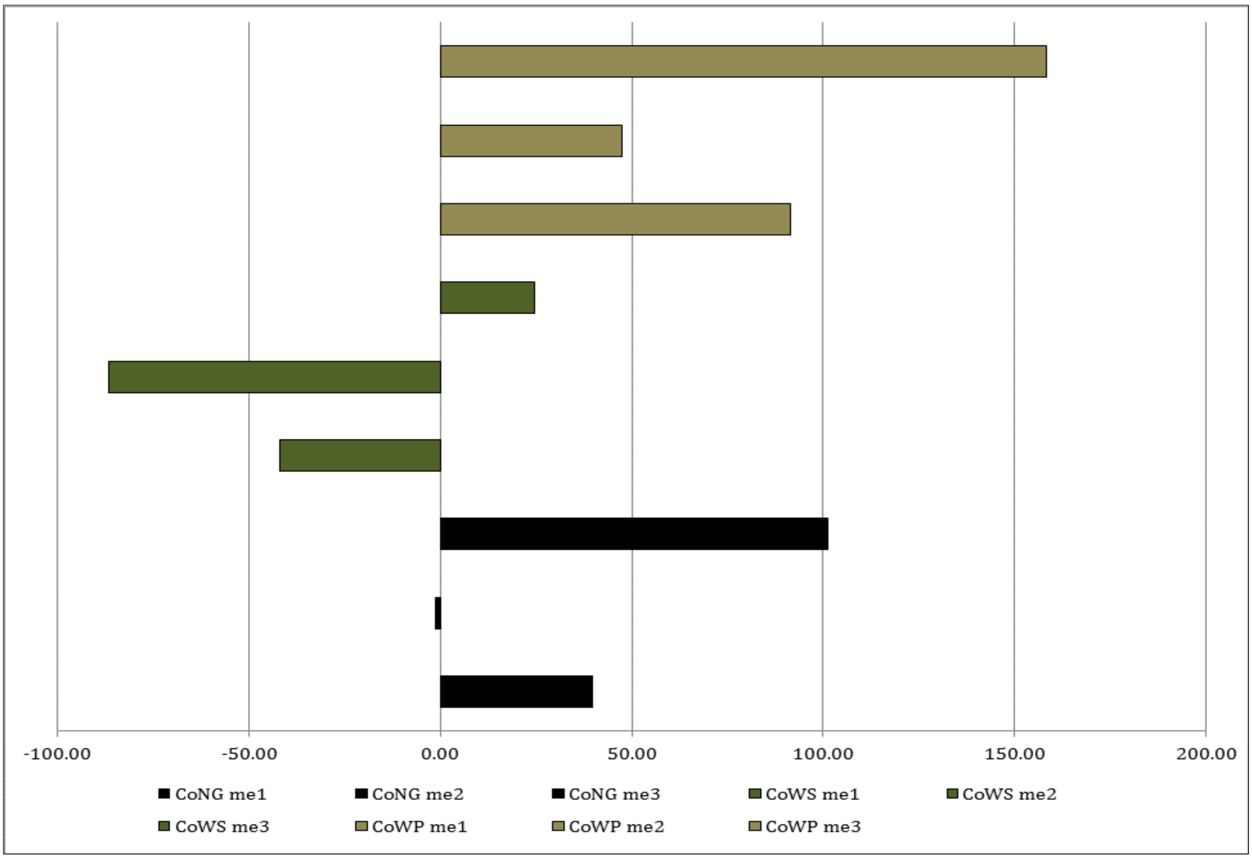

Figure 14: GWP (g CO_2-eq per MJ heat) in all Scenarios

In the case of wood pellets, the gross GWP is relatively higher than other two scenarios, because wood pellets are assumed to be imported and transported from Latvia to Denmark. Furthermore, energy inputs (diesel consumption in the processing of pellets, *see Table 8*) makes it more energy intensive and could have an effect in the GWP, which is discussed in section 4.3.3. The detail breakdown of the GWP related to every stages of energy conversions in both upstream and downstream process for every scenario are shown in Appendices 9-17.

Summarizing the effect: In every substitutable marginal electricity scenarios, CoWS shows higher efficiency in lowering down the GWP compared to CoNG and CoWP. Referencing back to the consequences of the straw removal as discussed in section 4.2, the removal of 1 t straw (85% DM) leads to a GWP of 135 kg CO_2-eq. But, if the life cycle impact of such removal is linked with its energy values to produce district heat in a CHP, it shows that use of such kind of crop residues leads to lower the GWP in all types of marginal electricity scenarios. For instance in me2, it leads to the net GWP of -86.54 g CO_2-eq/MJ heat. Hence, use of the straw not only substitutes the conventional source of energy such as NG, but also eventually leads to displace the environmental impacts associated with them, finally balancing the GHG effects of the straw removal. The net GWP of CoNG and CoWS as shown in Table 11 is the example of this particular benefit.

4.3.2. Acidification Potential

In the case of $CoNG_{me1}$, $CoNG_{me2}$ and $CoNG_{me3}$, acidification potential are estimated to be 2E^{-04}, -1.97E^{-03} and 7.06E^{-04} m^2UES/MJ heat respectively. Likewise, the AP related to 1 MJ of heat production in the scenarios $CoWS_{me1}$, $CoWS_{me2}$ and $CoWS_{me3}$ are 1.02E^{-02}, 7.86E^{-03} and 1.08E^{-02} m^2UES respectively. $CoWP_{me1}$, $CoWP_{me2}$, $CoWP_{me3}$, leads to AP as 2.13E^{-03}, -1.82E^{-04} and 2.72E^{-03} m^2UES respectively per 1 MJ of heat production (Figure 15).

Table 12: AP in the energy conversion process

	AP (m^2UES/MJ heat)								
	CoNG			CoWS			CoWP		
	me1	me2	me3	me1	me2	me3	me1	me2	me3
Upstream	2.39E^{-04}	2.39E^{-04}	2.39E^{-04}	6.41E^{-04}	6.41E^{-04}	6.41E^{-04}	1.83E^{-03}	1.87E^{-03}	1.87E^{-03}
Downstream	-3.94E^{-05}	-2.21E^{-03}	4.66E^{-04}	9.57E^{-03}	7.22E^{-03}	1.01E^{-02}	2.97E^{-04}	-2.06E^{-03}	8.45E^{-04}
Gross	7.89E^{-04}	7.89E^{-04}	7.89E^{-04}	1.09E^{-02}	1.09E^{-02}	1.09E^{-02}	2.77E^{-03}	2.81E^{-03}	2.81E^{-03}
Net Impact	2.00E^{-04}	-1.97E^{-03}	7.06E^{-04}	1.02E^{-02}	7.86E^{-03}	1.08E^{-02}	2.13E^{-03}	-1.82E^{-04}	2.72E^{-03}

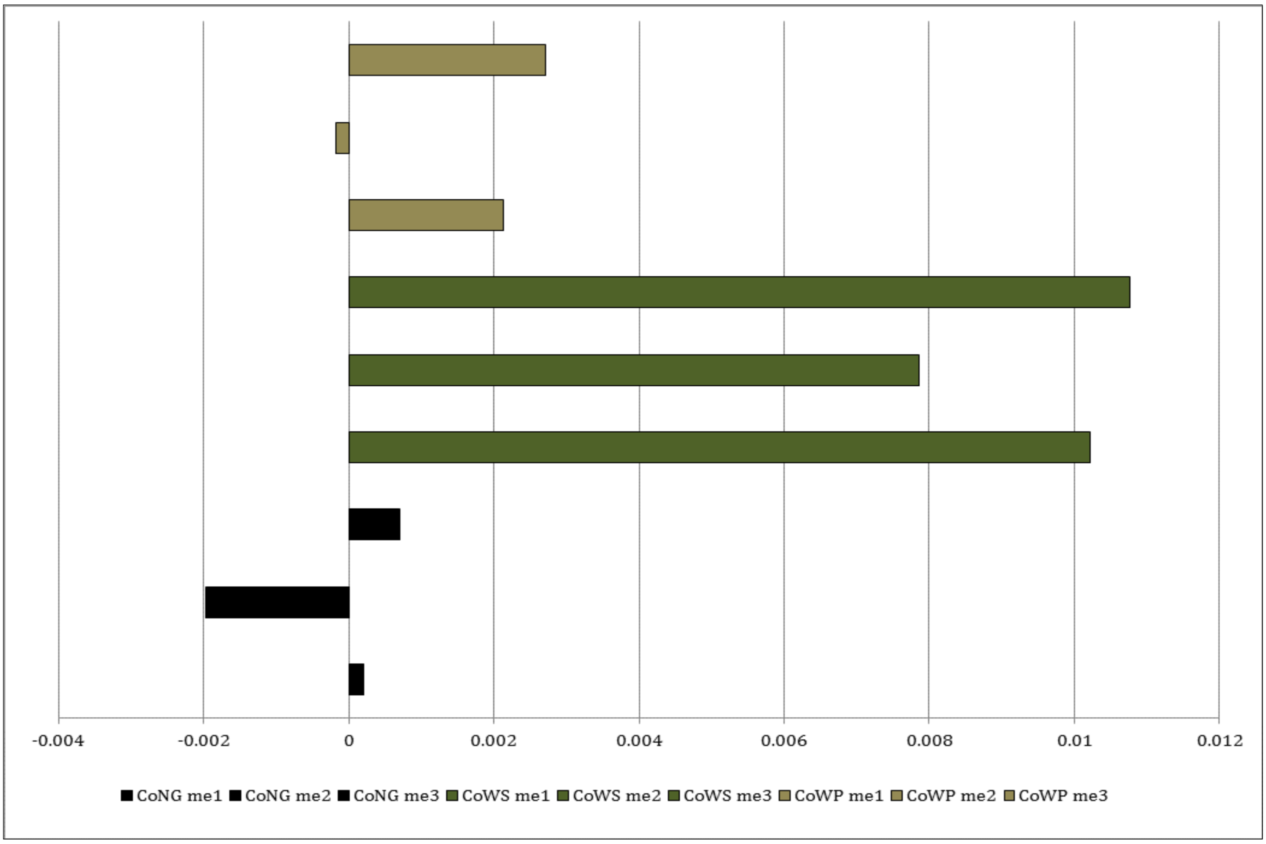

Figure 15: AP (m^2UES/MJ heat) in all Scenarios

Summarizing the effect: As discussed above and from the Appendices 9-17, the downstream process, particularly combustion is most responsible process that leads to increase the AP. The reason behind this is the liberation of acidifying elements such as NOx, HCl and SO_2 from the combustion. In all cases of marginal electricity, combustion of straw is found with more AP, compared to the combustion of other alternative fuels (Figure 15).

4.3.2. Eutrophication Potential

Table 13 -14 show the EP (aquatic and terrestrial) in the energy conversion process of the three different fuel scenarios. The estimated aquatic EP (expressed in g NO_3-eq/MJ heat) for $CoNG_{me1}$, $CoNG_{me2}$ and $CoNG_{me3}$ are 2.2 E^{-04},-1.4E^{-03} and 7E^{-03} respectively. Likewise, the terrestrial EP for the same scenarios are 8.11E^{-04}, 1.56E^{-04} and 3.49E-03 m^2 UES/MJ heat respectively.

The estimated EP (aquatic) in $CoWS_{me1}$, $CoWS_{me2}$ and $CoWS_{me3}$ are 0.127, 0.125 and 0.134 g NO_3-eq respectively per 1 MJ of heat production. Whilst for the similar scenarios, EP (terrestrial) is estimated as 6.23E^{-03}, 5.52E^{-03} and 9.14$E^{-03}$$m^2$UES/MJ heat respectively.

Similarly in the case of $CoWP_{me1}$, $CoWP_{me2}$, $CoWP_{me3}$ EP (aquatic) is estimated at 0.008, 0.006 and 0.015 gNO_3-eq for every 1 MJ of district heat production respectively. The estimated EP (terrestrial) for the similar Wood pellets scenarios are 4.46E^{-03}, 3.82E^{-03} and 7.44E^{-03} m^2 UES/MJ heat respectively.

Table 13: EP (aquatic) in the energy conversion process

	EP, aquatic (g NO_3-eq/MJ heat)								
	CoNG			CoWS			CoWP		
	me1	me2	me3	me1	me2	me3	me1	me2	me3
Upstream	0.002	0.002	0.002	0.125	0.125	0.125	0.008	0.008	0.008
Downstream	-0.002	-0.003	0.005	0.001	-0.0002	0.009	-0.0002	-0.002	0.007
Gross	0.008	0.008	0.008	0.141	0.141	0.141	0.016	0.016	0.016
Net Impact	0.0002	-0.001	0.007	0.127	0.125	0.134	0.008	0.006	0.015

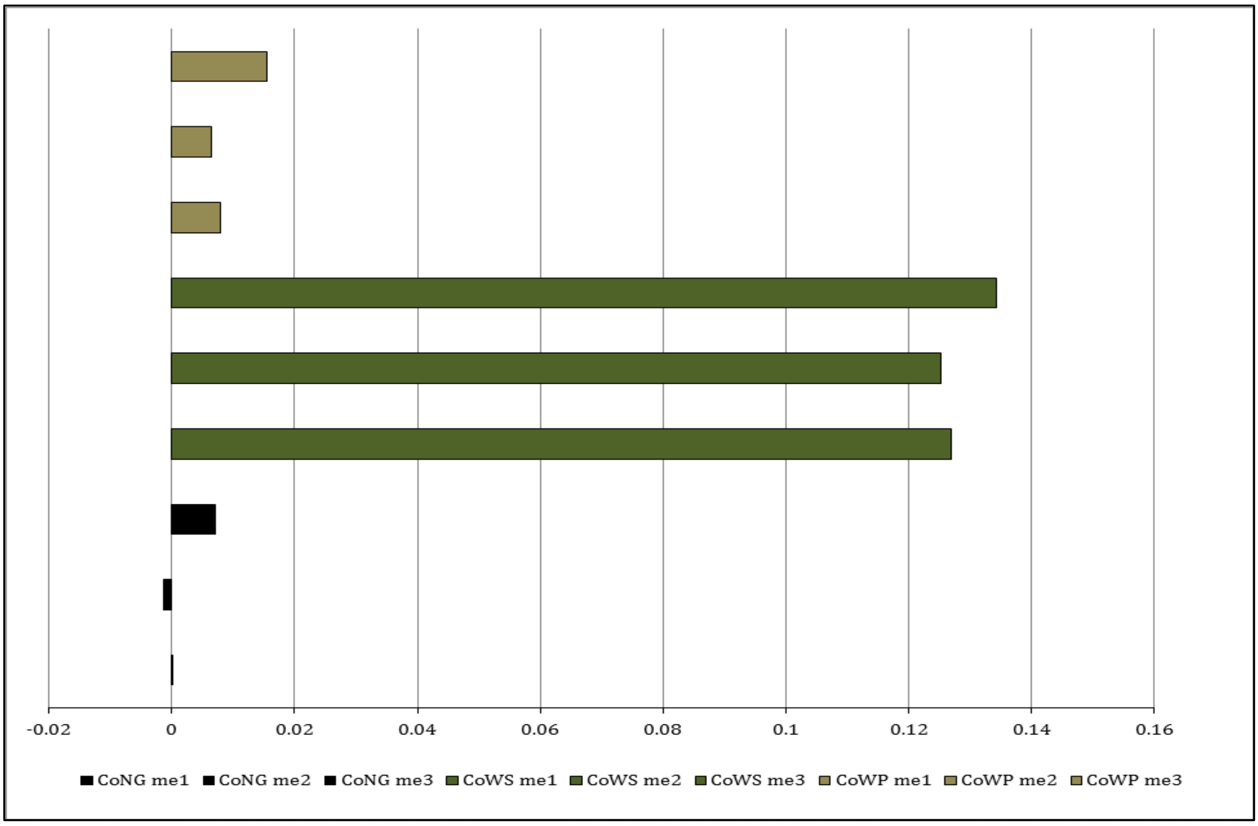

Figure 16: EP (aquatic) in g NO_3-eq/MJheat in all Scenarios

Both aquatic and terrestrial eutrophication potentials are higher in the case of CoWS, compared to CoWP and CoNG, and the latter hence has the least effect to an aquatic ecosystem (Figure 16-17).

Table 14: EP (terrestrial) in the energy conversion process

	EP, terrestrial) (m^2 UES/MJ heat)								
	CoNG			CoWS			CoWP		
	me1	me2	me3	me1	me2	me3	me1	me2	me3
Upstream	8.25E^{-04}	8.25E^{-04}	8.25E^{-04}	1.95E^{-03}	1.95E^{-03}	1.95E^{-03}	3.66E^{-03}	3.74E^{-03}	3.74E^{-03}
Downstream	-1.37E^{-05}	-6.69E^{-04}	2.67E^{-03}	4.28E^{-03}	3.57E^{-03}	7.19E^{-03}	7.97E^{-04}	8.58E^{-05}	3.70E^{-03}
Gross	3.58E^{-03}	3.58E^{-03}	3.58E^{-03}	9.23E^{-03}	9.23E^{-03}	9.23E^{-03}	7.46E^{-03}	7.53E^{-03}	7.53E^{-03}
Net Impact	8.11E^{-04}	1.56E^{-04}	3.49E^{-03}	6.23E^{-03}	5.52E^{-03}	9.14E^{-03}	4.46E^{-03}	3.82E^{-03}	7.44E^{-03}

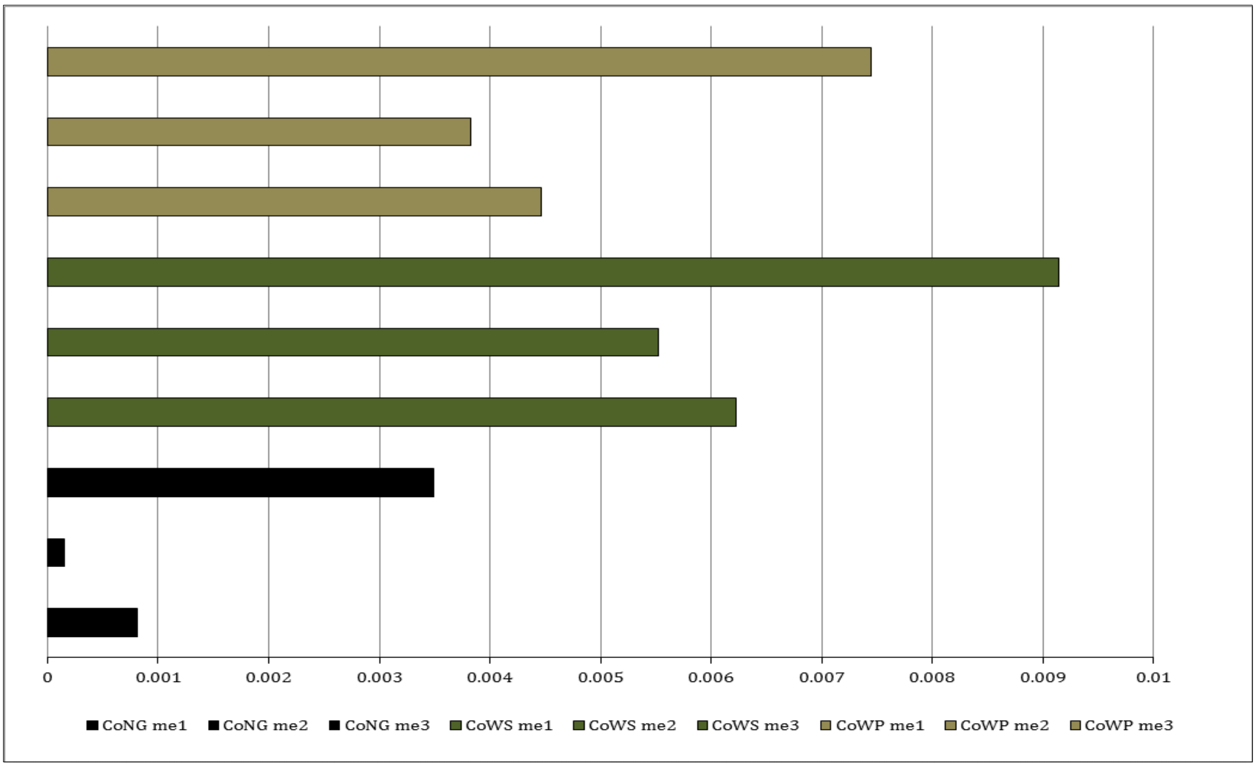

Figure 17: EP (terrestrial) in m^2 UES/MJ heat in all Scenarios

Summarizing the effect: Upstream process leads to higher EP (aquatic) in every scenario, and the straw fired district heat production has the highest impact compared to NG and Wood pellets. The reason behind having higher eutrophication in the case of straw is due to the emissions of nitrogen during the manufacturing process of compensating fertilisers, despite the effects of nitrate emissions from the application of compensating amount of fertilisers is reduced due to avoidance of N-build up due to removal of the straw (see LCI, Table 5). Wood pellets are assumed to be imported from the natural forest and it is assumed that the compensation of fertiliser is not required, which in turn would have to be considered if the pellets are assumed to be imported from the cultivated forest.

4.3.3. NRE Use

The gross primary energy consumption to produce 1 MJ of district heat in the scenario CoNG is 3.32 MJ-primary, which is higher by 36 and 9 folds than the gross NRE use in CoWS and CoWP respectively (Table 15). The net NRE for every 1 MJ district heat productions in CoNG with the substitutable marginal electricity me1, me2, and me3 are 2.5, 2.11 and 3.30 MJ-primary respectively. Displacement of fossil fuel consumption is higher if the substitution of coal and NG fired marginal electricity production take place, which leads to lower the net NRE use compared to the situation of displacing Wind power (see section 4.1 about the displaceable impact associated with marginal electricity).

In the same manner, CoWS_{me1} and CoWS_{me2} lead to higher fossil fuel saving in every 1 MJ of heat production. The NRE use in the former is -0.8 MJ-primary/MJ heat and in the latter scenario is -1.23MJ-primary/MJ heat, whilst it is estimated to consume additional fossil fuel at the rate of 0.07 MJ-primary for every unit MJ of heat production if the equivalent amount of Wind based power production is displaced from the total electricity mix. In the same manner, CoWP_{me1} and CoWP_{me2} leads to have the NRE use at -0.53 MJ-primary/MJ heat and -0.96 MJ-primary/MJ heat, and if wind power is displaced it is 0.34 MJ-primary/MJheat.

The energy intensity in the upstream and downstream sides of the district heat production in all scenarios are shown in Table 15, where it is found that due to co-products, downstream processes are less energy intensive then the upstream sides. Referencing back to the GWP and discussed in section 4.3.1 for the CoWP, it is evident that compared to the CoWS, the NRE use in the upstream side of energy conversions of the Wood pellets is higher (Table 15), which has an influence in the GWP. The detail breakdown of major processes involved in the upstream and downstream sides of the energy conversion along with their associated life cycle impacts are presented in Appendices 9-17.

Table 15: NRE use in the energy conversion process

	NRE Use (MJ-Primary/MJ heat)								
	CoNG			CoWS			CoWP		
	me1	me2	me3	me1	me2	me3	me1	me2	me3
Upstream	3.32	3.32	3.32	0.08	0.08	0.08	0.35	0.36	0.36
Downstream	-0.82	-1.21	-0.02	-0.88	-1.31	-0.01	-0.88	-1.32	-0.02
Gross	3.32	3.32	3.32	0.09	0.09	0.09	0.35	0.36	0.36
Net Impact	2.50	2.11	3.30	-0.80	-1.23	0.07	-0.53	-0.96	0.34

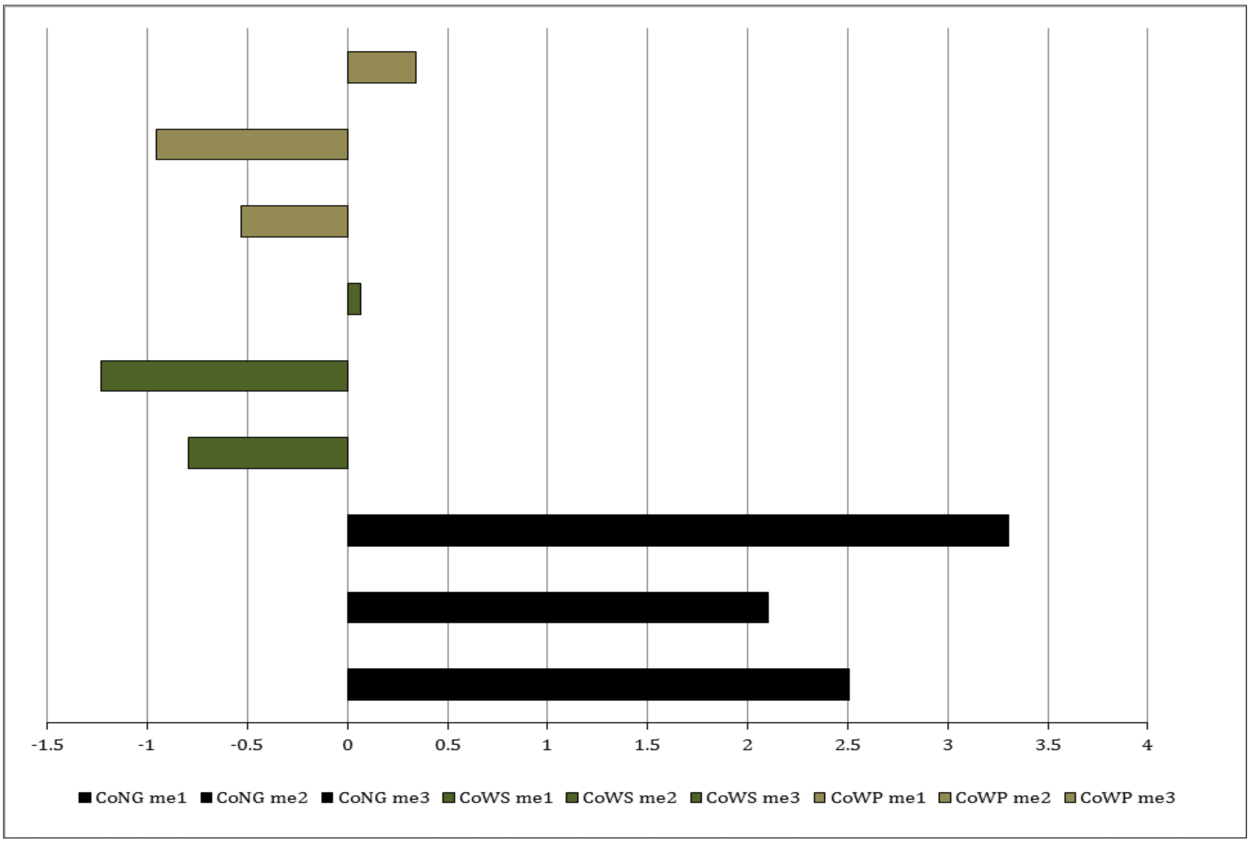

Figure 18: NRE Use (MJ-primary /MJ heat) in all Scenarios

Summarizing the effect: Straw fired district heat production is less energy intensive in the life cycle process of the energy conversions compared to the Wood pellets and NG. Displacement of coal as the marginal electricity further allows the straw fired heat production in CHP to be attractive option by increasing the savings in the fossil fuel consumption in relation to the entire life cycle process.

4.4. Environmental hotspots

In order to identify the environmental hotspots, every stage of energy conversions of the fuel alternatives is correlated with the respective gross environmental impacts. Environmental hotspots are defined as the most influential stages of energy conversion, which have higher contribution to increase the environmental impacts. The gross environmental impacts for all three fuel scenarios and their respective substitutable marginal electricity scenarios are discussed in section 4.3 (Table 11-15), and the impacts associated with the different stages of energy conversion are also presented in Appendices 9-17.

In addition to this, influence of the two co-products, electricity and fertiliser values in the slag, are also analysed based on the net impacts of 1 MJ of heat production, which helps to identify the significance of co-products of the system designed in this study.

4.4.1. CoWS

In the CoWS, straw removal is the major stage of energy conversion process to contribute in the GWP, which leads to have an effect of 83% of the gross GWP, followed by the collection and pre-processing (13%) and rest by other processes. All these proportions are in relation to the gross GWP associated with the life cycle process of producing 1 MJ of heat. Similarly, in regard to the AP, the combustion process is the most influential stage of energy conversion route contributing 94% of the gross impact and rest of the impact is followed by other stages of energy conversions.

Straw removal further has influential role in the EP (aquatic), which leads to cover 88% of the gross impact. In the case of EP (terrestrial), the combustion process is the most responsible stage of the energy conversions leading to have an effect of 78% of the gross impact, followed by the straw removal process 14%, 6% by collection and pre-processing and the rest is covered by other processes (Figure 19).

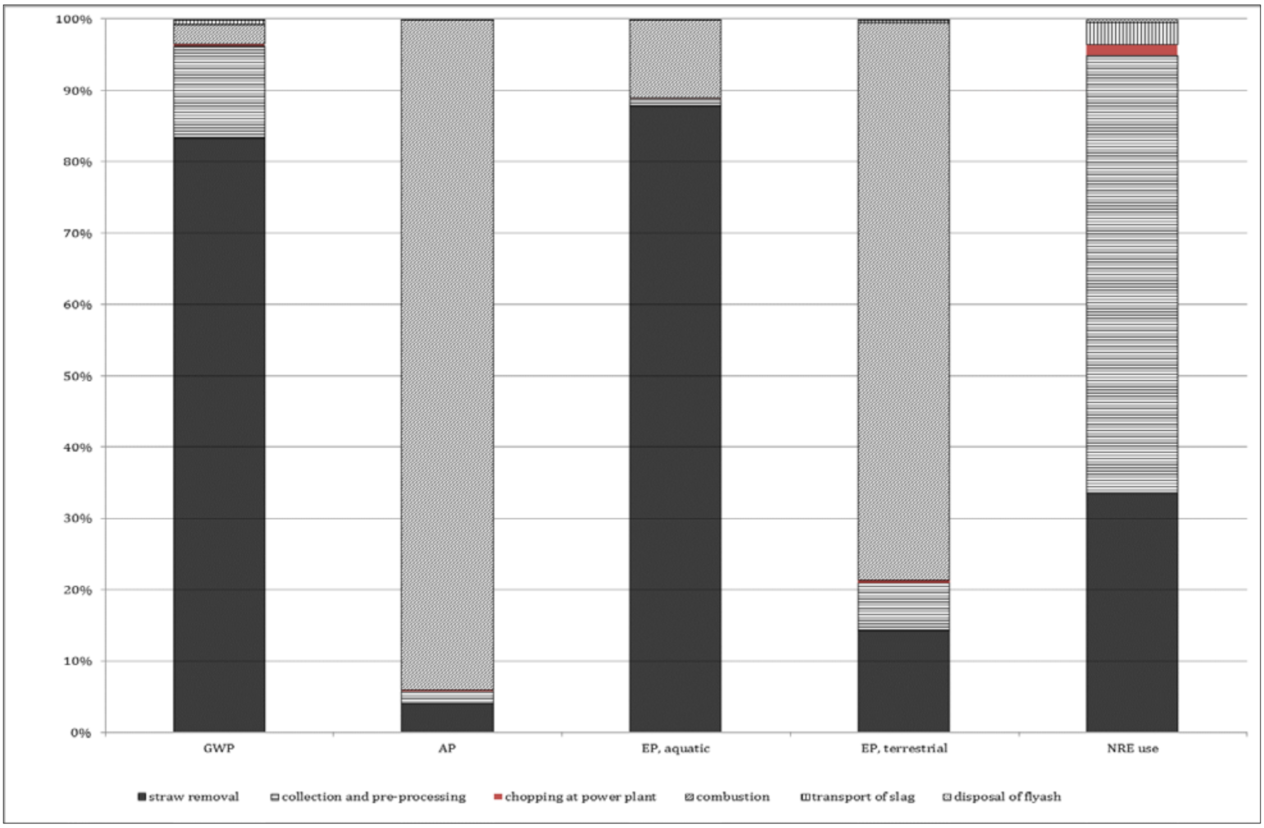

Figure 19: Energy conversion processes and their shares on the gross environmental impacts per 1 MJ of heat production

Regarding, consumption of fossil fuel in the entire chain of energy conversions, the collection and pre-processing of the straw is found consuming most of the primary energy required (i.e. 61%) of the gross NRE use, followed by the straw removal process covering 33%, transportation of the biomass with 14% and rest by other process as shown in Figure 19. 34% of the gross NRE use in the straw removal process is basically due to consumption of fossil fuel in the manufacturing of the estimated amount of the compensating chemical fertilisers (mass of fertilisers are shown in Table 5).

This reflects that the major environmental problem in the energy conversion of straw to produce district heat in a CHP are mainly associated with the processes such as straw removal process, collection and pre-processing, and combustion, having different levels of impacts in different impact categories (Figure 19).

In section 4.3, it is also discussed about how the co-products such as electricity and nutrient values of slag have tendency to avoid/reduce the environmental impacts. The potential avoidance of environmental impacts from the two co-products in the selected impact categories are shown in Appendices 13-15, where electricity is found most influential product to favor the production of heat, in particular fired with the straw in a cogeneration unit.

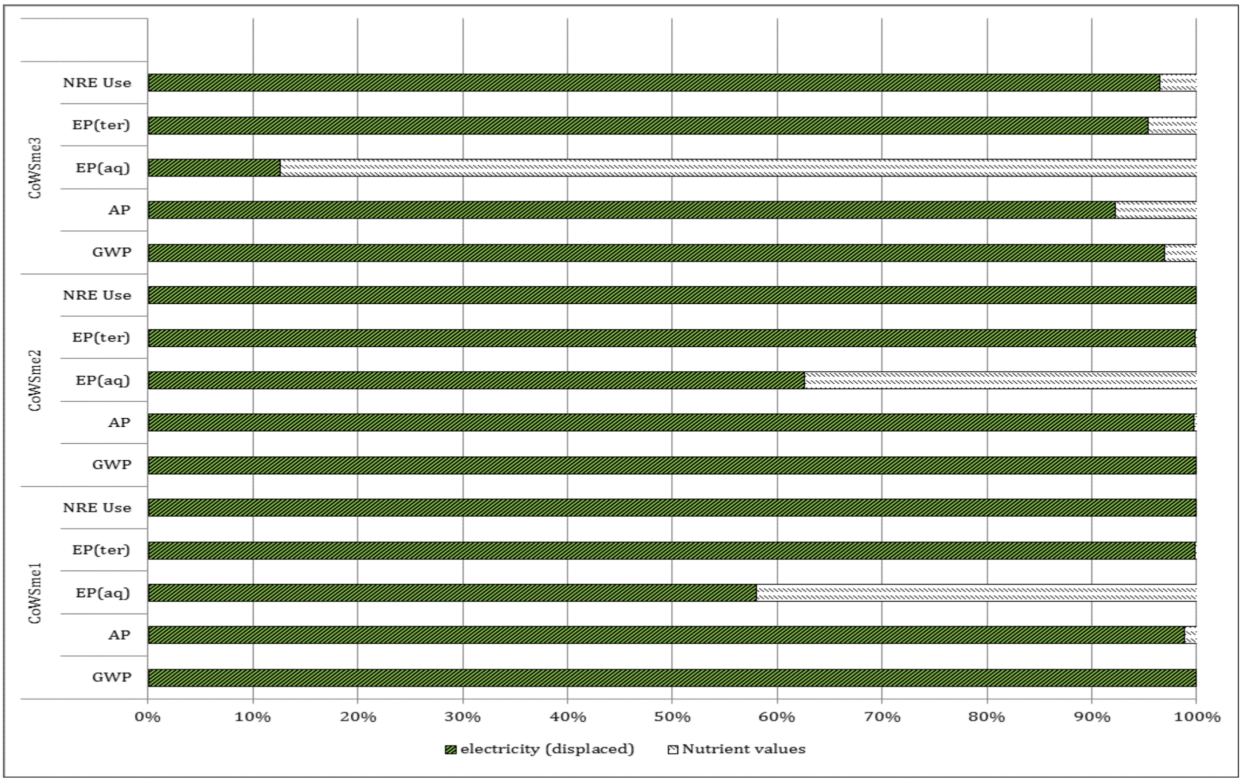

Figure 20: Share of co-products in the potential avoidance of environmental impacts of CoWS

Figure 20 describes about the how the co-produced electricity and nutrients values available in the slag reduce the environmental impacts in every 1 MJ of heat production. Electricity is found reducing most of the environmental impacts for all three Scenarios. In the case of $CoWS_{me3}$, the eutrophication (aquatic) is found potentially reduced primarily due to displacement of nutrients in comparison to the substitution of marginal electricity (wind power). The reason behind this is because of wind has less emission to the water, and impacts displaced in the marginal electricity substitution (me3) is lower than the displaced impacts because of nutrients produced from the system. Otherwise, for other impact categories, the displacement of marginal electricity has the most important role in lowering the environmental impacts. For instance, almost 100% of the displaced GWP is due to substitution of marginal electricity in the case of me1 and me2.

4.4.2. CoWP

Figure 21 shows the environmental hotspots in the energy conversion process of Wood pellets fired district heat production. Like in the case of consequence of removing the straw, the removal of forest residues in the CoWP leads to increase the GWP, which is primarily because the process limits the carbon sequestration potential that could have been possible if the wood stocks are not harvested from the forest. Hence, in the gross GWP, the average share of wood residue removal is 85%.

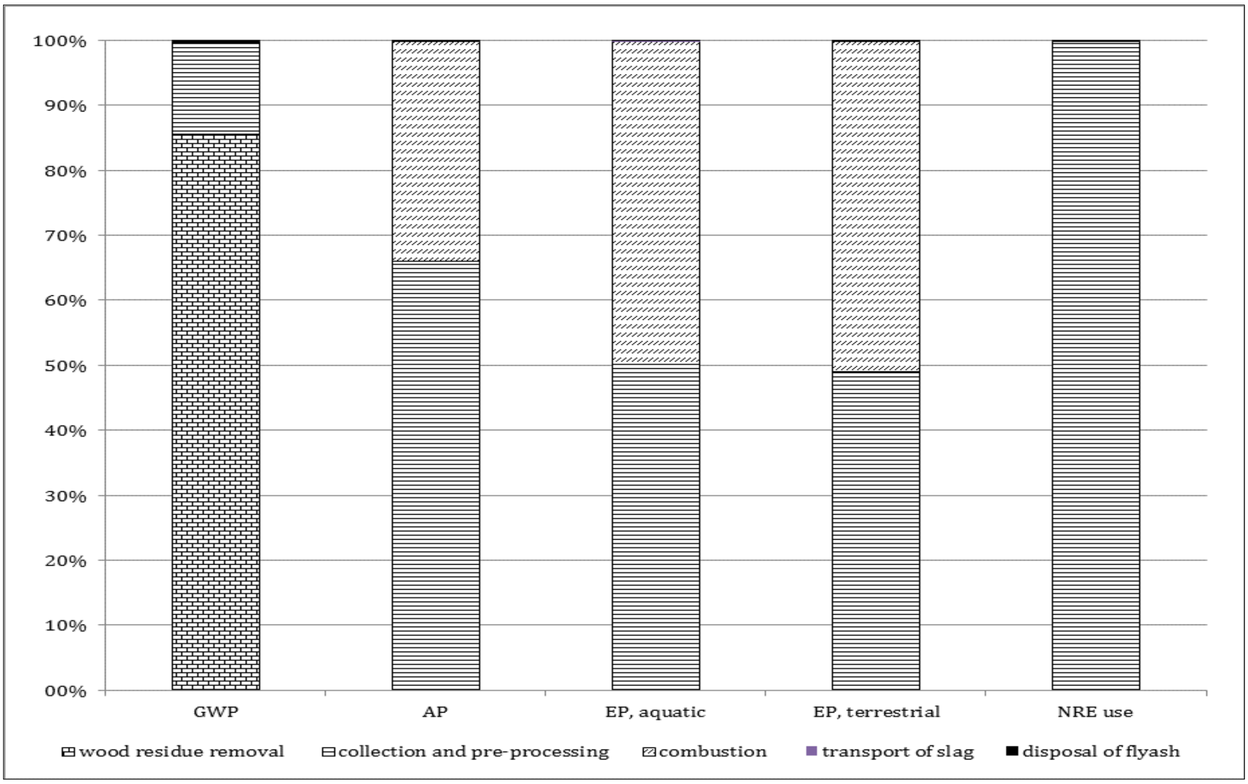

Figure 21: Energy conversion processes and their shares on the gross environmental impacts per 1 MJ of heat production

AP is primarily because of the effects related to emissions from the two processes: collection and processing, and combustion which contribute 66% and 34% respectively of the gross AP. In the same manner, both processes are found responsible to increase the EP (aquatic and terrestrial). Collection and pre-processing, and combustion of pellets are found contributing about 50% each in the gross EP (aquatic and terrestrial). Almost 100% of the fossil fuel consumption takes place in the collection and pre-processing of the pellets. The detail breakdown environmental impacts associated with each energy conversion process of Wood pellet based scenarios are shown in Appendices 16-18.

Similar to the CoWS, environmental performances for CoWP with me2 are better in comparison to other marginal electricity scenarios. The significance of co-production in lowering down the environmental impacts in the case of CoWP under different substitutable marginal electricity scenarios are shown in Figure 22.

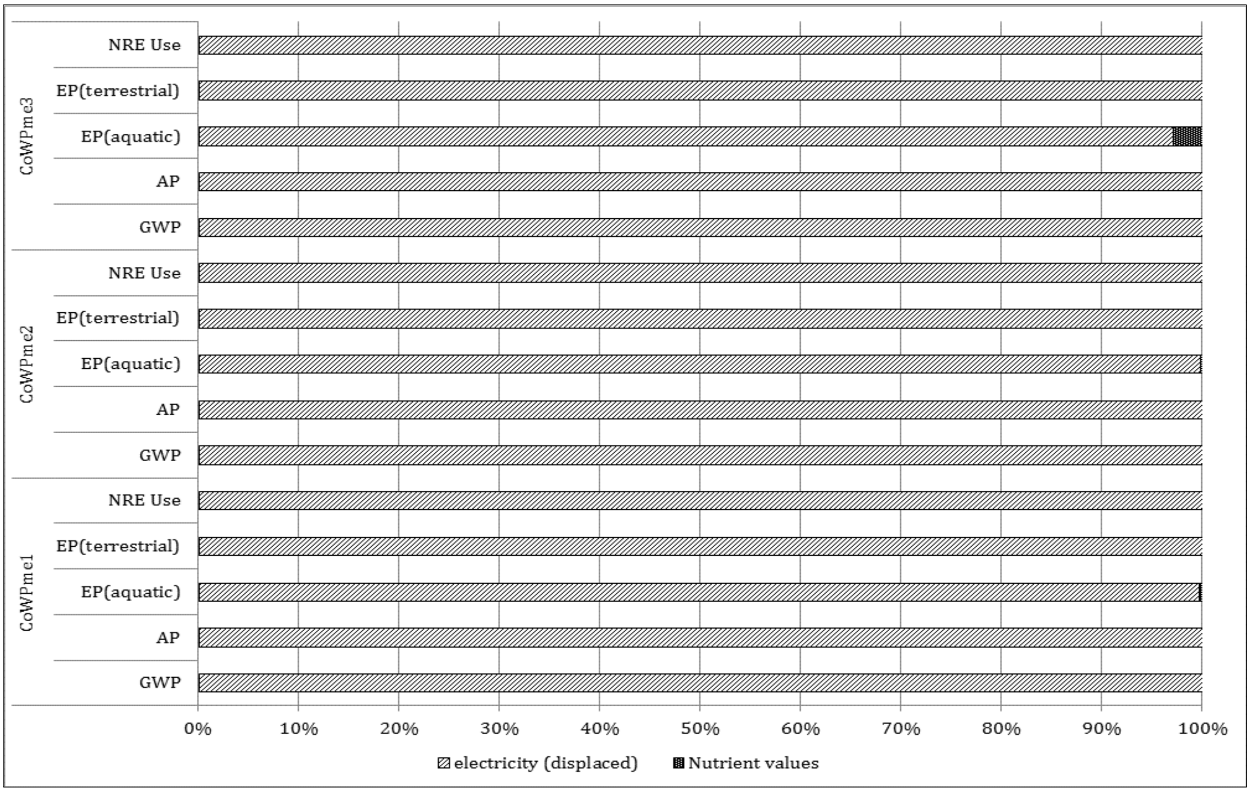

Figure 22: Share of co-products in the potential avoidance of environmental impacts of CoWP

4.5. Environmental Differences

The environmental differences refer the differences of environmental impacts between CoNG with respectively CoWS and CoWP. The environmental differences are assessed to understand about the environmental performances of replacing NG by straw and wood pellets to produce district heat in a cogeneration unit.

The net reductions in the GWP because of the adoption of the scenario CoWS instead of CoNG with marginal electricity scenarios me1, me2 and me3 are 82, 85 and 76 g CO_2eq respectively for every 1 MJ district heat production. The similar replacement leads to increase the acidification potential by an average amount of 0.01 m^{2}UES for every 1 MJ heat replaced.

In contrast, CoWP while replacing the CoNG to produce 1 MJ of district heat with marginal electricity scenarios me1, me2 and me3 is found leading to increase the GWP by 52, 49, and 57 g CO_2eq respectively. Likewise, in the case of replacing NG by wood pellets, it also leads to increase the AP by 0.002 m^{2}UES/MJ heat (Figure 23). This reveals that the AP in the wood pellets is relatively lower than the straw fired plant, but both biomasses have higher than the NG.

Likewise, for every 1 MJ of district heat production in $\text{CoWS}_{\mathbf{me2}}$ instead of $\text{CoNG}_{\mathbf{me2}}$, leads to increase EP (aquatic) by 0.13 g NO_3-eq, whereas the replacement taking place with CoWP leads to increase this potential by 0.01 g NO_3-eq. The increase in the EP (terrestrial) in the course of replacing CoNG by CoWS and CoWP to produce 1 MJ of district heat is 0.005 m^{2}UES and 0.004 m^{2}UES respectively.

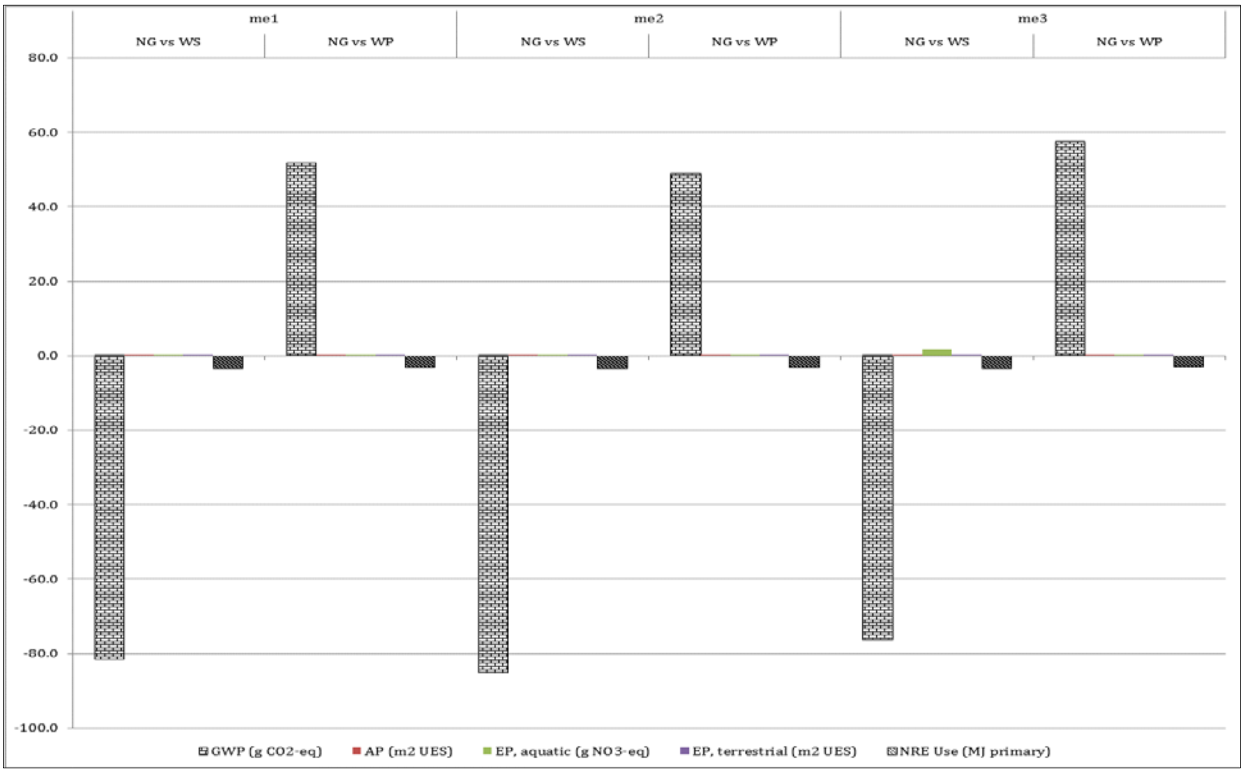

Figure 23: Environmental differences due to substitution of NG by respectively straw and Wood pellets fired cogeneration unit (per 1 MJ heat)

The replacement of NG by the straw leads to increase the fossil fuel savings by 3.3, 3.34 and 3.23 MJ -primary for every 1 MJ of replaceable district heat production, with marginal electricity scenarios me1, me2 and me3 respectively. The similar replacement with CoWP for the respective marginal electricity scenarios are 3.04, 3.06 and 2.96 MJ-primary. The savings in the fossil fuel from the replacement of NG with the straw instead of wood pellets is higher by 1.09 fold.

From the environmental differences, it is found that straw based district heat production could be regarded as favorable option compared to Pellets and NG, if fossil fuel savings and reductions in GWP are considered as decision making parameters. But, when EP (both aquatic and terrestrial) and AP are considered, straw is less favourable compared to pellets and even to that of NG (Figure 23).

4.6. Economic Evaluation

The NPV of CoWS_{me2} is estimated as 114 M€, which is almost 2 and 1.3 times lower than the CoNG_{me2} and CoWP_{me2} respectively. The annual cost of operation estimated in terms of EAC in CoWS_{me2} is 9 M€, whilst for CoNG_{me2} and CoWP_{me2} are 18 and 12 M€ respectively (Table 16). These indicators reflect that the investors are expected to save 109 M€, if the assumed ideal capacity of 10 MW straw fired CHP plant is built instead of NG fired, in the discounted period of 20 years. The savings because of the replacement of CoNG_{me2} from the installation of CoWS_{me2} is 1.4 times higher than savings estimated from CoWP_{me2}.

Likewise, the equivalent annual cost of operation of CoWS_{me2} and CoWP_{me2} is estimated to be lower by 50% and 33% respectively than the CoNG for the similar marginal electricity scenarios. The net levelised cost of heat production (see section 3.7) is estimated with an assumption that co-produced electricity displaces the LPC of coal based marginal electricity production. The displaceable production cost of marginal electricity in every 1 MWh of district heat production is estimated at 38 €. This leads to a net LPC of 89 €, 27 €, and 46 € per 1 MWh of district heat production.

Table 16: Economic evaluation on the fuel choices in relation to district heat production

Parameters	CoNG_{me2}	CoWS_{me2}	CoWP_{me2}
NPV (M€)	223	114	146
EAC (M€)	18	9	12
Gross LPC (€/MWh)	127	65	83
Cost of displaced electricity (€)	38	38	38
Net LPC (€/MWh)	89	27	46
Net LPC (DKK/MJ)	0.185	0.056	0.094

The reason behind the higher cost of heat production in NG and WP are primarily due to higher fuel cost. The fuel cost represents 96% of the gross LPC in NG based cogeneration unit and 83% in the Wood pellets (Figure 24). Furthermore, the fuel price for NG includes energy and CO_2 taxes, whereas straw and pellets does not, as discussed in section 2.6.

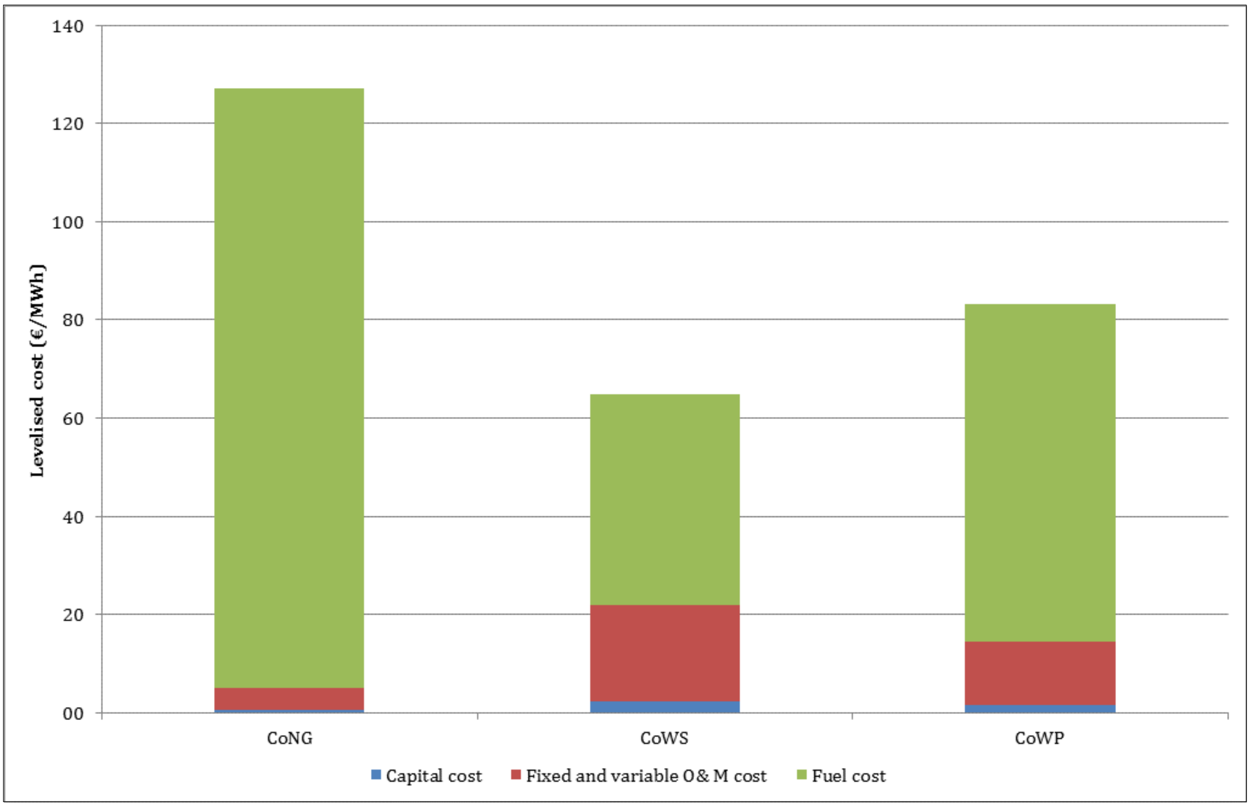

Figure 24: Shares of capital cost, and O&M costs to the gross LPC (CoNG)

Figure 25 shows about the variations in the production cost of district heat along with the changes in the fuel cost. It is found that with every additional 5% increment in the projected fuel prices (as shown in Figure 9), the net LPC of district heat in $CoNG_{me2}$, $CoWS_{me2}$, $COWP_{me2}$ increases at the rate of 14%, 16% and 15% respectively.

For the similar fuels, with every 5% decrease in the fuel prices, the net LPC decreases at an average rate of 14%, 17% and 16% for CoNGme2, $CoWS_{me2}$, $COWP_{me2}$ respectively (Figure 25). From the economic evaluation, CoWS is regarded to be better alternative compared to the other two scenarios, and in particular if substitutes the coal based marginal electricity production.

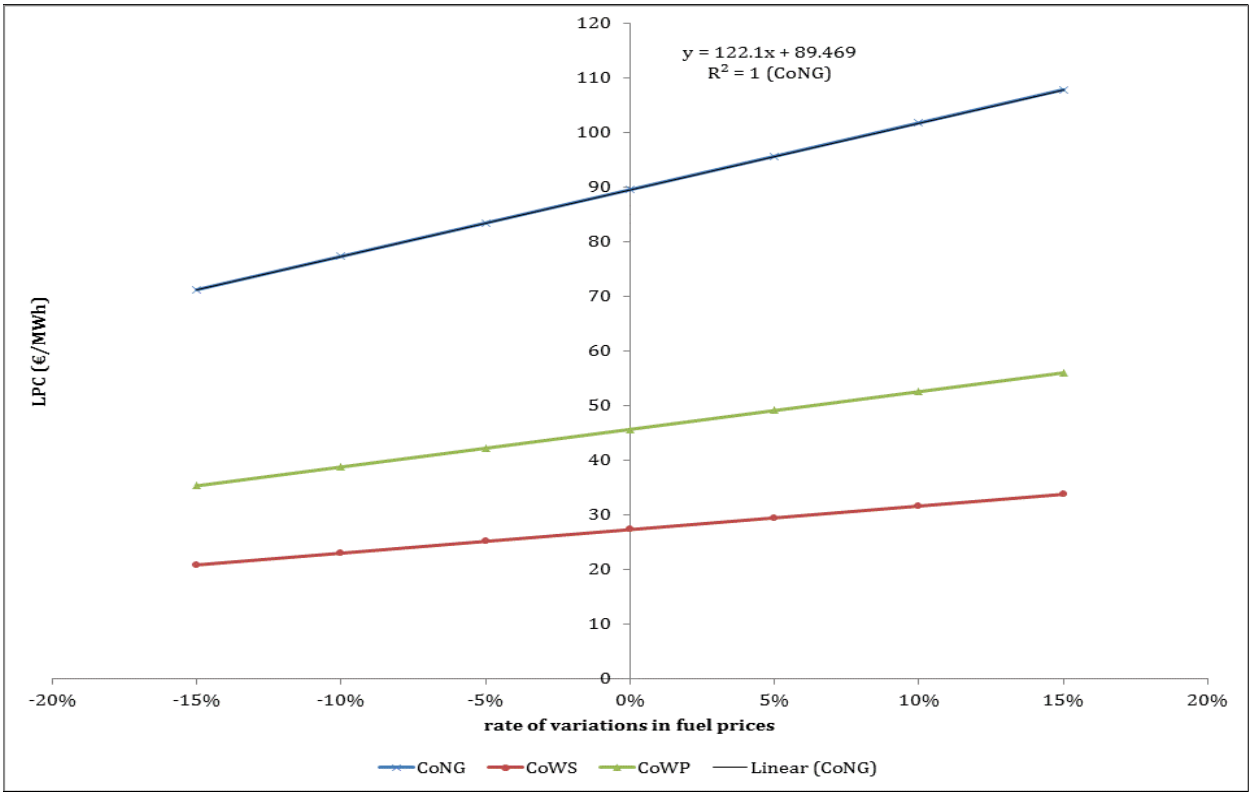

Figure 25: Sensitivity of net LPC due to variations in the fuel prices ($\mathrm{CoNG_{me2}}$, $\mathrm{CoWS_{me2}}$ and $\mathrm{CoWP_{me2}}$)

4.7. Up-scaling the assessment with respect to a larger heat demand

Environmental performances of fuel choices in relation to 1 MJ of district heat production as discussed in the earlier sections are up-scaled to a larger heat demand. The equivalent share of NG in the Danish gross district heat production observed in 2011 is set as basis for up-scaling the environmental impacts. In 2011, NG based district heat production was 35 PJ. Despite this amount of NG fired district heat production may not continue in the future, the objective of up-scaling in reference to it, is to overview how the replacement of NG by biomass would relate with potential land use, and also to over view the environmental differences in the life cycle process of district heat production at a larger scale.

Figure 26 shows the environmental effects of replacing 35 PJ of NG fired district heat production by wheat straw. Despite the straw has a significant role to reduce the GWP and to increase the savings of fossil fuel, some of the issues and opportunities in the replacement of NG fired heat production by straw are as follows:

- With the calorific value of 14.5 GJ/t, the total quantity of straw required to produce 35 PJ of district heat is 3999 Mt. As discussed in section 2.2 (Table 3), the total straw production (based on cereals) in Denmark in 2011 was 3.16 Mt, which is far below the required quantity as mentioned above. Furthermore, the above mentioned 3999 Mt of the straw represents alone from the wheat crop.

- This bring out attention that if 3.16 Mt of straw produced in 2011 required 962 (‘000 ha) of the area (Table 3), then for 3999 Mt of straw, it requires 42% of the total agricultural area of the country. From the total agricultural area of the country (Table 1) and further from the distributions of crop area (Table 2-3), it is evident that in 2011 the total cereals area of the country covered 51% of the total agricultural area. Hence, if 100% of such replacement of NG fired district heat production is required to be considered in future, it leads to probable direct and indirect land use changes (iLUC). This has tendency of displacing other marginal agricultural production. However, effect of iLUC is not relevant if the available amounts of the straw that can be used for energy purpose are considered for heat/power production, but if the consumption of straw exceeds the limits of its availability then it could have significant impacts on the availability of the straw for other applications (such as animal feed), and consequently could demand more area to cultivate the wheat crop.
- Another consequence of the removal of 3999 Mt of straw is limiting soil carbon sequestration, which leads to increase the GWP at an equivalent rate of 542 Mt CO_2-eq per year. Despite this constraint, the life cycle impacts of utilising the removed straw to produce the replaceable 35 PJ of NG fired district heat production would further lead to GWP at -2963 Mt CO_2-eq per year (if coal is assumed as the substitutable marginal electricity) (Figure 26). Hence, from the stand point of GWP, the substitution of NG fired heat production by straw is favourable to lower the GHG emissions level of the country.
- From the similar replacement, it is estimated that 116 PJ-primary of fossil fuel per year can be saved, if coal is assumed to be displaced marginal electricity.
- As discussed before, however straw fired district heat production is more favourable from GWP and NRE use, it has higher AP and EP compared to NG (Figure 26).

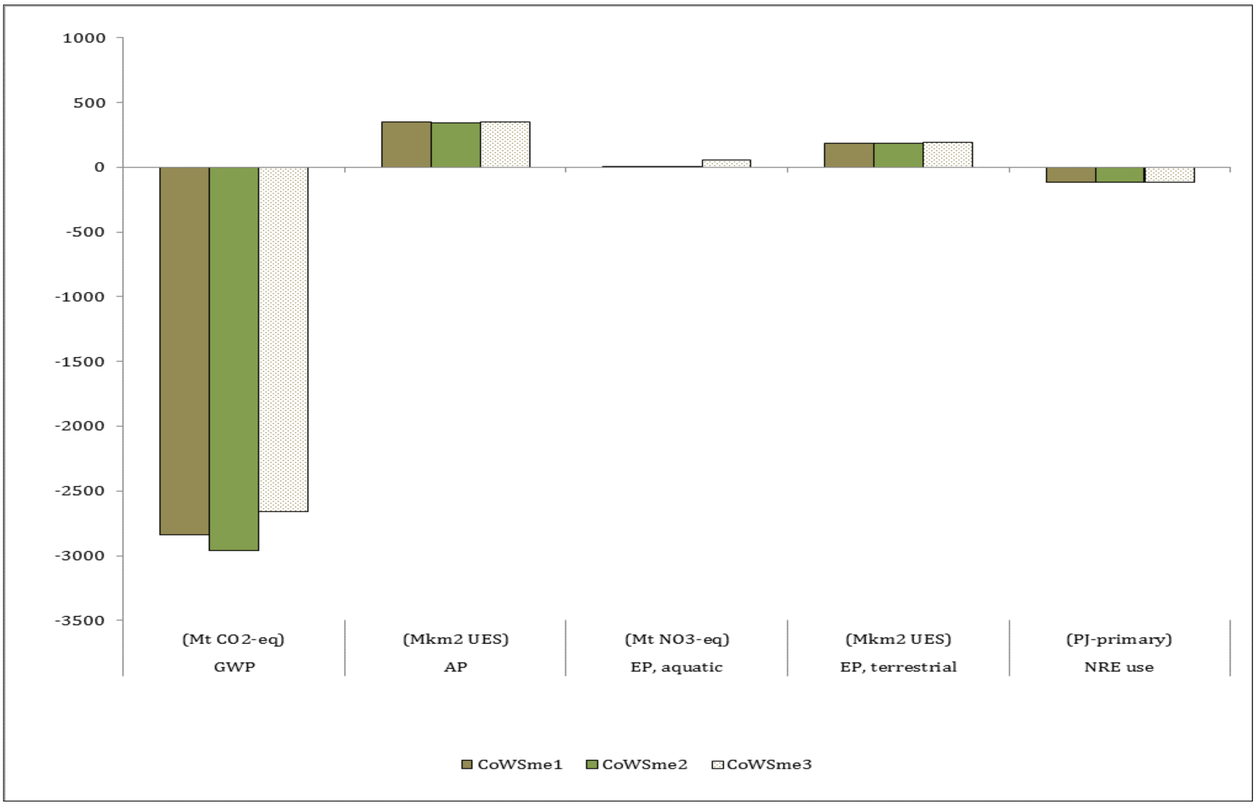

Figure 26: Effects of replacing 35 PJ of NG fired district heat production by the straw

Likewise, Figure 27 shows the life cycle impact of replacing the 35 PJ of NG fired district heat production by imported Wood pellets. The replacement of NG by the Wood pellets has relatively lower rise in the EP and AP compared to the straw. But the substitution leads to increase the GWP by 1695 Mt CO_2–eq per year and savings in fossil fuel is 1.09 times lower than that of the replacement occurs with the straw. Some of the important aspects of such substitution are;

- With the calorific value of 17.5 GJ/t, the total quantity of Wood pellets required to produce 35 PJ of district heat is 3313 Mt. This result to exacerbate the effect of increasing GWP associated with the removal of 3313 Mt of the wood residues, which is estimated at 0.44 Mt CO_2-eq/year.
- Despite the above consequence, in the entire life cycle process (from removal of forest residues to consumption), the replacement of NG would lead to GWP of 1695 Mt CO_2-eq/year, if coal is assumed as the displaced marginal electricity (Figure 27).
- The replacement leads to save 107 PJ of fossil fuel in the entire life cycle process. Impacts associated with other marginal electricity scenarios are shown in Figure 27.

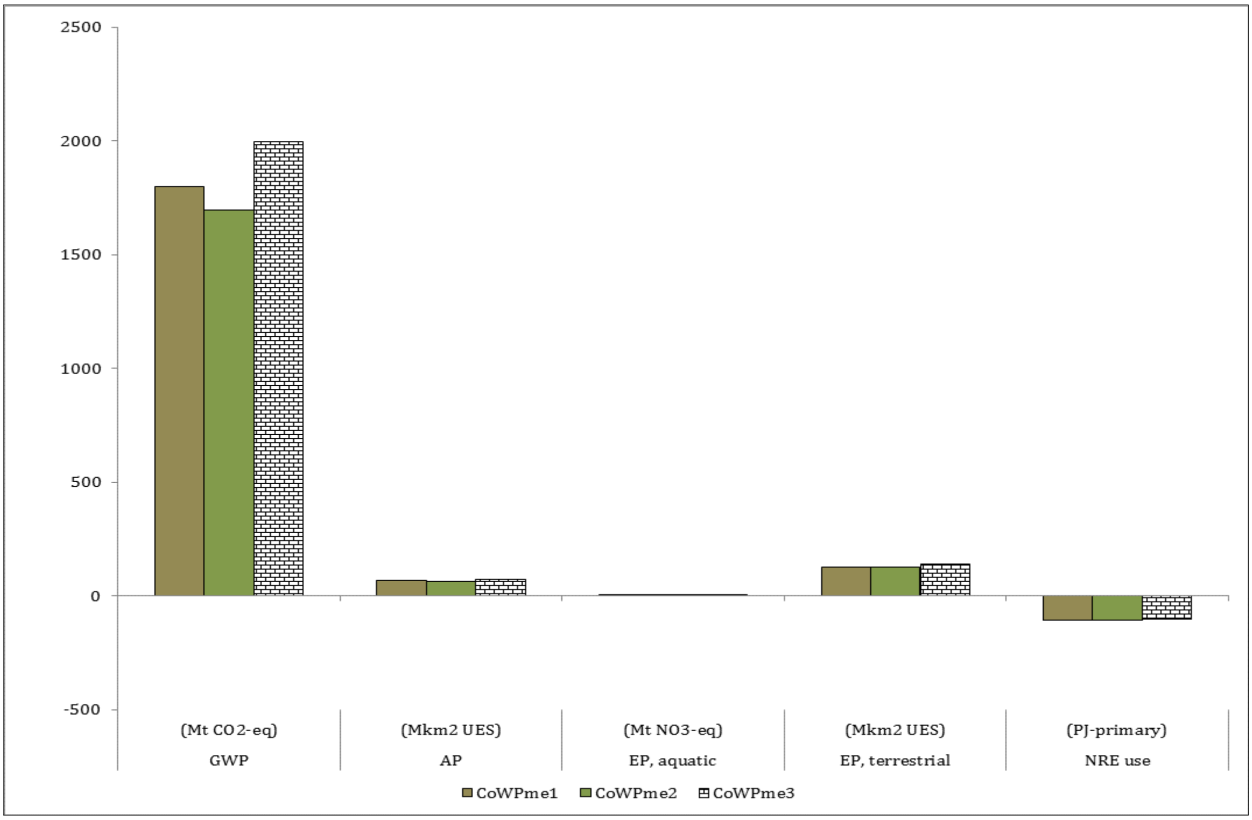

Figure 27: Effects of replacing 35 PJ of district heat production based on NG by Wood pellets

4.8. Issues and Opportunities

Issues and opportunities discussed in this section are based on the life cycle impacts associated with fuel choices and the economic evaluation presented in section 4.5 and 4.6 respectively. It also follows with possible means of addressing the identified environmental issues in relation to the straw removal for heat production, which are based on some of the past experiences and researches in the relevant issues.

4.8.1. Possible means of addressing the issues of EP and AP

Straw fired district heat production could lead to significant reductions in GWP and NRE use in the entire life cycle process. But at the meantime, AP and EP are found among the challenging issues while considering the straw as a fuel alternative for district heat production compared to the alternatives NG and Wood pellets. Environmental hotspot (see section 4.4, Figure 19 and 21) divulges that the EP (aquatic) is basically due to straw removal process. In general nitrate leaching takes place due to N content in the chemical fertilisers. But in the case of removal of straw the soil N buildup is also avoided. But this opens an opportunity to investigate if the effect of nitrate leaching from other process involved in the straw removal stage can be addressed by any other additional activities, such as intercropping and integration of catch crop after harvesting the straw.

Likewise, the terrestrial EP is mainly due to emissions of NOx in the combustion process, and the AP is mainly associated with the direct emissions such as HCl, SO_2 and NOx resulting from the combustion process (see Table 6).

These direct and indirect emissions are major factors that negatively influences the selection of straw as a fuel input for heat production, however, some of the possible solutions to reduce/control these impacts are discussed as follows;

Eutrophication Potential (aquatic and terrestrial)

The higher concentration of nitrate in water leached from soils is related to polluting the ground water, lake and other water ecosystem (Kirchmann et al. 2002). Improvement of agricultural management practices is one of the solutions for controlling the nitrate leaching (McLenaghen et al. 1996; Kirchmann et al. 2002). The management practices could include integration of winter "catch crops", since the catch crops normally decrease leaching loss by absorbing much of the mineralised N back into the organic pool (Martinez and Guiraud 1990), compared to the situation when the field is fallow leading to higher nitrate leaching (Eriksen and Thorup-Kristensen 2002). Furthermore, application of animal manure also supports in reducing the nitrate leaching compared to that would occur with inorganic fertilisers (Bouwman et al. 2002).

In the case of removing the straw, such kind of crop integration in the next cropping cycle could help in reducing the nitrate leaching, thereby controlling the aquatic EP. In addition to this such catch crops may supplement the need of additional biomass either for energy purposes or for animal feed. Despite these possible solutions, the economic viability of such integration is necessary to investigate before coming into such conclusion. Furthermore, LCA of such expanded systems could also be carried out to investigate to what level EP can be controlled because of such integrations (catch crops, use of manure etc).

Terrestrial eutrophication could be controlled by improved combustion system, so that NOx liberated during the combustion process can be controlled. It is discussed in the following section.

Acidification Potential

AP is estimated to be higher in straw fired district heat production compared to wood pellets (see Figure 15). Pehnt (2006) has also reported that emissions of chlorine, sulphur and NOx are higher in a straw-fired heating plants compared to short rotation wood. As shown in Table 6 (in the case of straw) and Table 8 (for wood pellets), both SO_2 and NOx are higher in the former compared to the latter fuel. The higher concentration of such acidifying substances in the direct emissions thus lead to higher AP compared to a forest wood. Furthermore, it is more triggered from the emissions related to inorganic fertiliser applications and other material inputs during the processing of the biomass.

Emissions of SO_2 and NO_x resulting from the combustion depend on a number of factors such as: heat content of a fuel, sulphur content and sulphur retained in the ash, and most importantly the combustion conditions (Graus and Worrell 2007). One of the possible means of controlling the acidification at a technological level is adopting the desulphurisation technology (EC 2006). Generally, desulphurisation technologies such as, the wet scrubber is found able to reduce the SO_2 emissions at the rate of 92%–98%, and the spray dry scrubber technology reduces at the rate of 85-92% (Kaminski 2003; EC 2006). These technologies are generally designed to reduce the SO_2 emissions of fossil fuel having higher sulphur content (EC 2006).

Similarly, NOx emissions are reported being controlled by adopting modifications in the combustion process such as, separating the combustion process in stages, which partially delays the combustion process and results in a cooler flame that suppresses thermal NO_x formation (EC 2006). There are other possible alternatives to lower the NOx emissions such as combustion in low excess air, and recirculate part of the flue gases into the combustion air, which prevents NOx formation (Graus and Worrell 2007). These technologies are gaining momentum in the Nordic countries (Graus and Worrell 2007). Flue gas condensation technologies is also popular for straw firing technologies in Denmark, and is reported to increase the thermal efficiency with 5-10% and reduces SO_2 emission to a minimum level (energinet.dk 2012). Likewise, NOx emissions may be reduced at the rate of 60-70% by adopting a non-catalytic reduction (SNCR) technology, which would cost 0.1 M€ (capital) and 400 €/tNOx (operational cost) for a district heating plant of 4-8 MW (energinet.dk 2012).

4.8.2. Resource competition and economic perspectives

Attention on the use of biomass in the future renewable energy goal of Denmark is very high, and the country has also aimed to produce additional 10 Mt of bioenergy without substantially affecting the agro ecosystem (Dalgaard et al. 2012). Biomass is potential source of energy in heat and power production, despite this, when the distribution of straw fired power plants in the last decades are observed, it reveals that they are not gaining proper momentum, which would have been required to support the strategy of integrating higher shares of renewable energy in the total energy mix of the country (Ea Energy Analyses 2010).

For instance, as shown in Figure 2, of the gross district heat production of Denmark, straw fired power plants have merely increased from 5% to 7%, whereas the Wood has increased from 4% to 19% (Danish Energy Agency 2011). This indicates that the locally available biomass, such as straw is yet to be up-scaled in the total energy mix of the country, including district heat production. It is also relevant from the economics of district heat production since compared to NG and Wood pellets, straw is relatively economical as discussed in section 4.6, and most importantly can be regarded attractive fuel options from the perspective of life cycle impacts of its energy conversions.

The slow momentum in the expansion of straw fired district heat production may also indicate that there are some barriers in its optimum utilisation. In this context, Ea Energy Analyses (2010) reported that the barrier is primarily associated with the economic perspectives (particularly with respect to biogas), as well as availability of alternative technologies/fuels in the energy market such as biogas and other energy crops. Ea Energy Analyses (2010) further highlights that despite the price of straw is lower compared to other available biomass, the handling and transporting process makes straw less convenient compared to wood chips and pellets. The density of the biomass is important parameter as it influences the conveniences of collecting, transporting, storing and for feeding into the combustion chamber. This in turn have influence to the overall efficiency of energy conversion (Natarajan et al. 1998). Based on these arguments, production of straw pellets could support to mitigate these issues associated with the density. Despite there is also wide scope of pelletisation of straw, the environmental performances of it in relation to similar scope as presented in this thesis could be concluded only from the LCA in its energy conversion chains.

Nevertheless, if the expected increase in the price of woody biomass (Wood chips and Pellets) as reported by the Danish Energy Agency (see Figure 9) are considered in the future shares of biomass sources then the prospects of utilising the crop residues might be an justifiable option compared to NG and even compared to Wood pellets. For instance, in section 4.6, it is revealed that the net levelised cost of producing 1 MJ of district heat in a straw fired cogeneration unit is lower by 69% and 41% compared to NG and wood pellets respectively.

Most importantly, the future energy strategy of Denmark demands higher penetration of renewable energy, and within it there is need of diversifying the renewable sources (Lund and Mathiesen 2009). The necessity of renewable energy diversification also entails about the need of increasing the consumption of biomass. At the meantime biomass resources can be regarded insignificantly limited if the existing land use pattern of Denmark is considered

(Østergaard et al. 2010). In this issue, crop residues such as straw can play significant role in such renewable energy diversification and also satisfying the necessity of maximising the consumption of storable forms of energy. This conjunction of biomass energy could play a vital role in fulfilling the localized and short term energy demand of the country, without affecting the agricultural system of the country, provided that the consumption is remained within the threshold limits of its availability.

Another important aspect is also about the understanding of potential competition among available biomass sources to fulfill different enduse energy requirements. This is important from the perspective of potential increase in the demand of biomass for more ”valuable” fuels for transport as expected in the Danish future energy mix (Hvelplund et al. 2011; Kwon and Østergaard 2012). In such situation the demand of straw might be much higher in the energy conversion chain of 2nd generation bioethanol, which might lead to create less attention towards its use in heat and power sector, or may have competition between each other. Nevertheless, to some extent this potential competition could be mitigated through the integration of a biorefinery value chains in the energy system. This could be another future perspective, where economic and environmental efficiency in relation to the production of different main products and co-products (including heat and electricity) in a biorefinery value chains can be investigated.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Summary and Conclusions

The main aim of this study is to assess the life cycle impact of producing 1 MJ of heat in a wheat straw fired CHP plant. With this scope, the assessment covers the energy conversion processes, commencing from the straw removal, collection and preprocessing, combustion and finally to the management of fly ash and bottom ash. Environmental performances of straw as a fuel input is further compared with the NG and wood pellets. In this study, straw is regarded as the domestic source of renewable energy in Denmark and wood pellets is assumed to be imported from a natural forest of Latvia. On the basis of results and discussions carried out in this thesis, summary and conclusions on the choice of fuel inputs in the district heat production are discussed as follows.

5.1.1. Environmental Perspective

The environmental perspectives covers the environmental consequences associated with the straw removal, and further assessing in relation to the production of heat using the removed straw.

5.1.1.1. Consequences of straw removal

Consequences of the straw removal are related to limiting the soil C sequestration potential and also to the necessity of compensating the nutrient values which also gets removed along with the straw. With these consequences, removal of 1 t straw (85% DM) leads to following environmental impacts:

- GWP: 135 kg CO_2-eq
- AP: 2.84 m^2 UES
- EP (aquatic): 0.78 kg NO_3-eq
- EP (terrestrial): 8.37m^2 UES
- NRE use: 185 MJ-primary

Environmental hot spots in the process of straw removal are as follows;

- Changes in the GWP are due to constraining the soil carbon sequestration potential compared to the situation if alternatively the straw is left on the field. This contributes to 87% of the gross GWP estimated for the straw removal process, and the remaining is covered by manufacturing process of chemical fertilisers, which should be compensated with the removal of straw.

- AP is primarily associated with the manufacturing process of compensating amount of chemical fertilisers, covering 60% of the gross impact, and rest are related to the emissions associated with the straw removal process (primarily because of the emissions from the compensating chemical amount of fertilisers).
- EP (aquatic) is primarily due to manufacturing process of compensating fertilisers. But, the 100-years Soil C sequestration potential, which is avoided due to straw removal is 118 kg CO_2-eq. This avoidance of soil C sequestration further correspond to the avoidance of related soil N-build , which is estimated at -23.45 g NO_3-eq for every 1 t straw removal (85% DM).
- EP (terrestrial) is primarily because of straw removal process, covering 64% of the total impact to terrestrial ecosystem and rest from the emissions of nitrogenous compound during the manufacturing process of compensating fertilisers.
- Almost 100% of the NRE use is due to manufacturing process of compensating fertilisers.

5.1.1.2. Straw utilisation as a fuel alternative in district heat production

The environmental performances in relation to the utilisation of removed straw for producing heat in a cogeneration unit (if coal is assumed as the substitutable marginal electricity) are summarized as follows. The values in the parenthesis represent the gross environmental impact (i.e. if co-products of the system are not accounted). Hence district heat production in a straw fired CHP plants leads to:

- Net GWP of -86.54 (25.86) g CO_2-eq/MJ heat
- Net AP of 0.008 (0.011) m^2UES/MJ heat
- Net EP (aquatic) of 0.125 (0.141) g NO_3-eq/ MJ heat
- Net EP (terrestrial) of 0.006 (0.009) m^2UES/MJ heat
- Net NRE use of -1.23 (0.088) MJ-primary/MJ heat

Of the gross life cycle environmental impacts, environmental hotspots are in relation to following energy conversion processes;

- GWP is basically due to effect of straw removal process, representing 83% of the gross impact in the life cycle process of straw combustion in a cogeneration unit. Collection and pre-processing covers 13% of the gross impact and rest by other processes involved.
- AP is primarily related to emissions from the combustion process, representing 94% of the gross impact.

- EP (aquatic) is mostly due to effects of straw removal process representing 88%, and followed by combustion process covering 11% of the gross impact
- EP (terrestrial) is basically due to NOx emissions from the combustion process and also from the removal of straw, representing 78% and 14 % respectively of the gross impact.
- 61% of the gross NRE is due to consumption of fossil fuel in the stage of collection and pre-processing of the biomass, whereas 34% are involved due to effects of straw removal (in particular due to NRE use in the manufacturing process of compensating fertilisers), and rest by other process such as transportation of the biomass, fly ash and bottom ash.

Improvement in agricultural management practices could control the aquatic EP. Similarly, with the use of desulphurisation technology to reduce the SO_2 emission and SNCR technology to lower the NOx emission helps in controlling the AP and also controlling the terrestrial EP resulting from higher concentration of NOx and limiting the availability of Nitrogen (N).

5.1.1.3. Replacement of NG fired district heat production

Wheat straw as a fuel alternative shows better environmental performances if NG fired heat production is replaced by the straw compared to the imported pellets. It has better opportunity to reduce the GWP and increase the fossil fuel savings in the entire life cycle process of energy conversions compared to the wood pellets. For instance, if coal is assumed as the substitutable marginal electricity, the reduction in the GWP due to replacement of NG by straw fired in a CHP to produce the district heat is 85 g CO_2-eq/MJ heat, whilst if replaced by imported wood pellets it increases at the rate of 49 g CO_2eq/MJ heat. But from the perspectives of AP and EP, substitutions to NG fired district heat production has lower additional effect to the agro ecosystem compared to the straw fired production, and also for the same impact categories wood pellets possess better results compared to the straw.

5.1.2. Economic Perspectives

Straw fired in a CHP is relatively better than the NG and imported wood pellets. The LPC of district heat with fuel alternatives NG, straw and Wood pellets are 0.025, 0.008 and 0.013 €/MJ heat respectively.

5.1.3. Conclusion from the Article-I

Straw fired district heat production is found better in a CHP and a boiler, compared to natural gas. In the case of producing heat in a boiler, the GWP and NRE use are 23.73 g CO_2-eq/MJ heat and 0.13 MJ-primary/MJ heat respectively. The AP while producing heat in a boiler is 0.008 m^2UES/MJ heat. Likewise, aquatic and terrestrial EP per 1 MJ heat production is 0.09 g NO_3-eq and 0.01 m^2UES respectively. Due to co-produced electricity, environmental impacts are significantly lowered if district heat is produced in a CHP.

5.2. Recommendation and Perspectives

Wheat straw as a fuel alternative is found an attractive option from the stand point of GWP and NRE use, but has adverse impact on the natural ecosystem in the name of eutrophication and acidification. In the life cycle process of energy conversion, EP aquatic is found primarily as a consequence of leaching of nitrates due to process involved in fertilizer applications and production. The environmental hotspots in the life cycle impact of straw utilisation also reveals about the other opportunities that can increase the attraction towards straw as a fuel alternative. These opportunities are associated with the potential reductions in the environmental impacts in different stages of energy conversions. For instance, the collection and pre-processing stage is found contributing much to the gross GWP and NRE Use in the life cycle process of heat production. From these aspects, this study highlights on the following potential research perspectives;

- Assessment of environmental performances in the case of applying animal manure instead of chemical fertilisers to fulfill the requirement of compensating nutrient loss. This assessment could lead to understand about the changes in the EP and AP in the energy conversion processes of the straw.
- Assessment of environmental performances, if fuels for the transportation and pre-processing of the straw are based on renewable sources.
- Assessment of environmental performance of biorefinery, where all the above mentioned aspects can be included in terms of main product and co-products of the system. It could further demand the LCA of wheat or other biomass based biorefinery value chains, where heat/power is among the spectrum of products and co-products of the system.

From this study, it is found that substitutable marginal electricity has a significant influence to the environmental performances of cogeneration unit. At the meantime, if Wind power is assumed as the marginal electricity, the net environmental performances is found less attractive compared to the Coal and NG. This reflects that the penetration of biomass fired cogeneration unit in the future energy system should ensure that displacement of polluting marginal technologies takes place, instead of replacing relatively more environmentally friendly technologies such as Wind power.

Most importantly it could be interesting to investigate the life cycle impact of utilising the straw for other purposes such as animal feed and building materials, and compare to its fuel values. Similarly, LCA of straw as a feedstock for biorefinery could be another areas of further investigation.

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APPENDICES

Appendix 1: Glossary of terminologies

Allocation: Allocation is the partitioning and distribution of an item over several other items (Weidema 2000).

Avoided Product: Avoided product is the determining co-product of the displaced process and therefore typically of higher value (and often also larger in quantity) than the dependent co-products (Weidema 2000) and can potentially substitute other products in the market (Contreras et al. 2009).

Gross heat output: It is the heat produced considering the heat content of the fuel (feedstock) and thermal efficiency of the combustion system

Eutrophication: Eutrophication is regarded as undesired increase in biomass production in aquatic and terrestrial ecosystem because of high nutrient inputs, and results to changes in biodiversity (Finnveden and Potting 1999; Brentrup et al. 2004). Terrestrial ecosystem, mainly affecting the higher plants is caused due to Nitrogen as the major limiting nutrient, when concentration of NOx and NH_3 increases in the ecosystem (Brentrup et al. 2004).

Net heat output: It is defined as "Gross heat output minus energy (heat and electricity) required during the process of biomass drying and combustion of feedstock in the power plant".

NRE: Non- renewable energy use is considered as the primary energy required (fossil fuel) in different processes of life cycle analysis carried out in this study.

Soil carbon sequestration: It refers to the increasing soil organic content through the transfer of atmospheric CO_2intoa prolonged period of time and storing securely to prevent immediate re-emission (Lal 2004).

Appendix 2: Electricity Mix of Czech Republic , including domestic production and imports

Materials/fuels	CezchRepublic	Unit
Electricity, hard coal, at power plant/CZ U	0.061861	kWh
Electricity, lignite, at power plant/CZ U	0.45911	kWh
Electricity, oil, at power plant/CZ U	0.003652	kWh
Electricity, natural gas, at power plant/CENTREL U	0.04016	kWh
Electricity, industrial gas, at power plant/CENTREL U	0.000891	kWh
Electricity, hydropower, at power plant/PL U	0.023478	kWh
Electricity, hydropower, at pumped storage power plant/PL U	0.006154	kWh
Electricity, nuclear, at power plant/UCTE U	0.2855	kWh
Electricity, at cogen ORC 1400kWth, wood, allocation exergy/CH U	0.006223	kWh
Electricity, at cogen with biogas engine, allocation exergy/CH U	0.001343	kWh
Electricity, production mix DE/DE U	0.001612	kWh
Electricity, production mix AT/AT U	0.000115	kWh
Electricity, production mix SK/SK U	0.005296	kWh
Electricity, production mix PL/PL U	0.10441	kWh

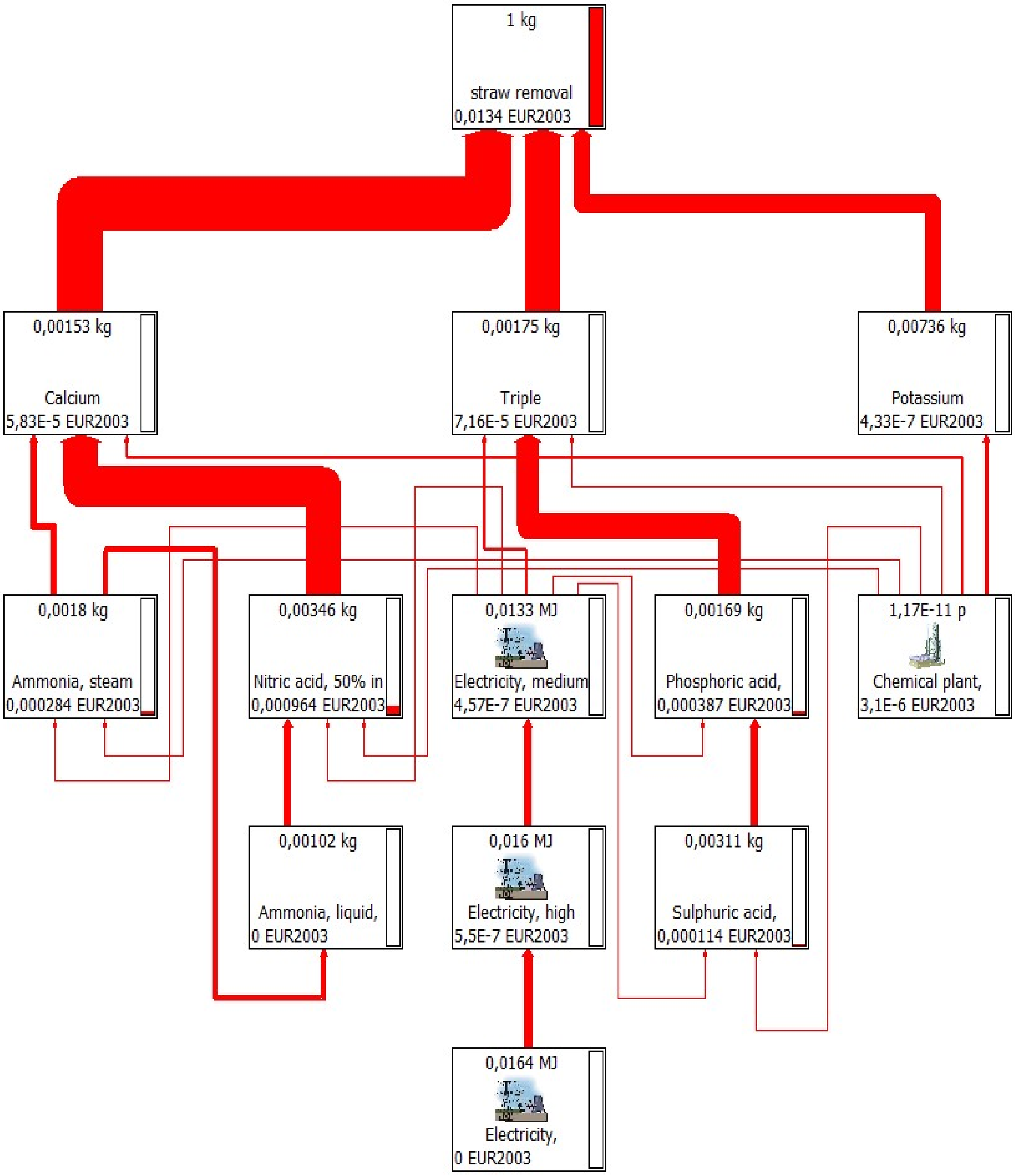
Source: (Ecoinvent Centre 2010)

Appendix 3: Emissions factors of fuels

GHGs	Straw$_1$	Wood Pellets[1]
	g/GJ of fuel input	
CH_4	< 0.5	< 2.1
N_2O	1.4	< 0.8
SO_2	47	< 1.8
NOx	131	69
HCl	46	< 0.9

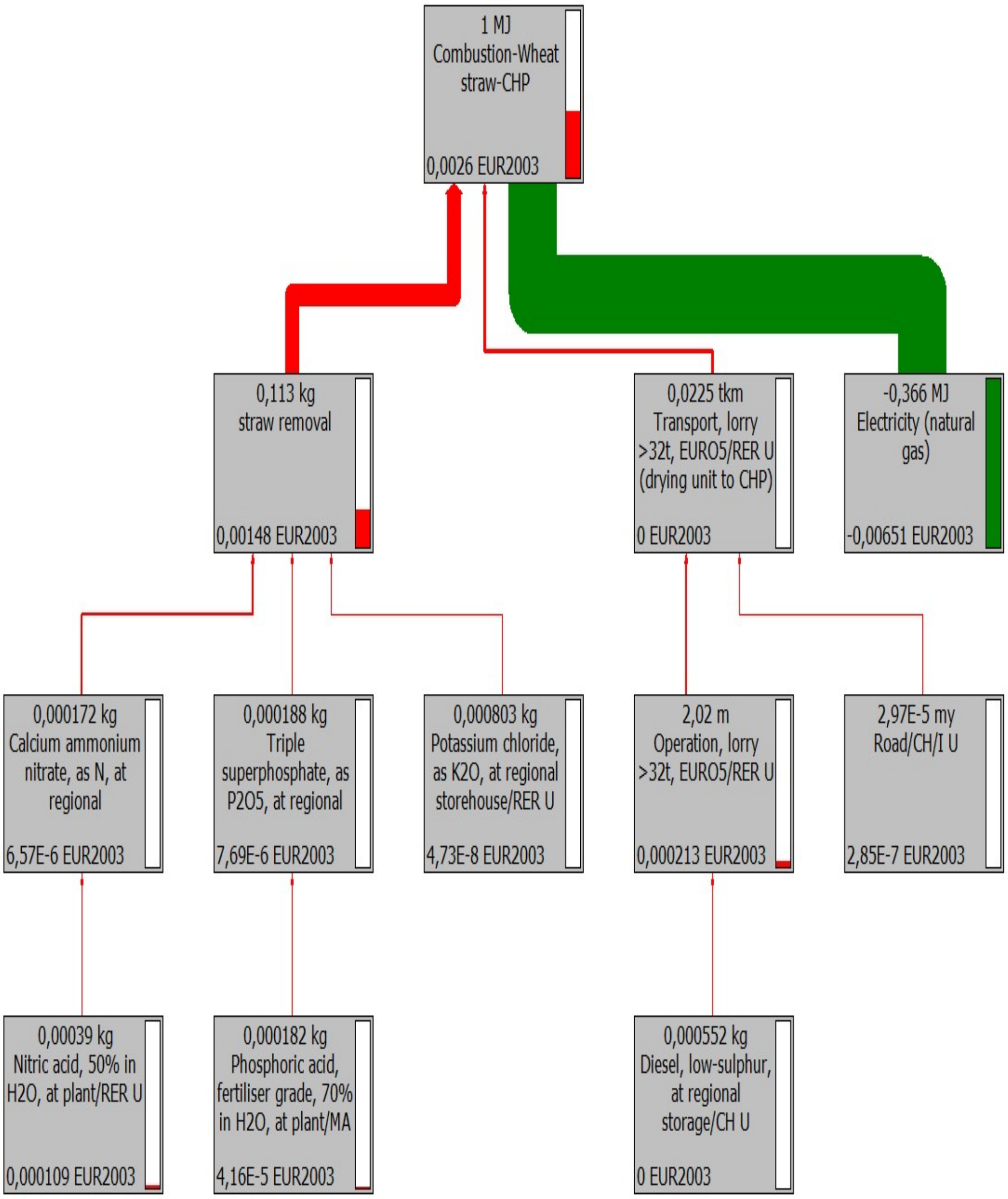
[1] *Sources:(Nielsen and Illerup 2003) and (Nielsen 2004)*

Appendix 4: Products' Networks for straw removal



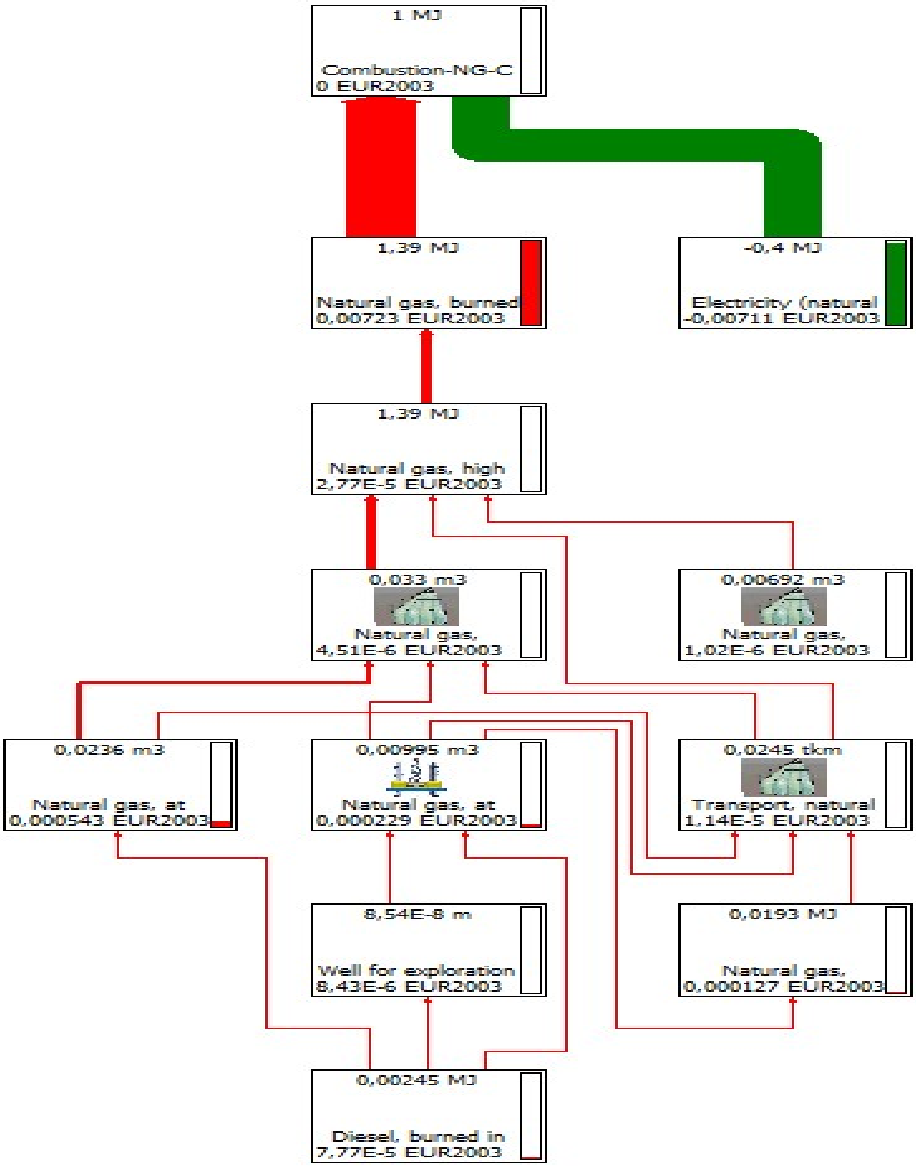
Source: Modeling in SimaPRO.

Appendix 5: Products' Networks for COWS$_{me1}$



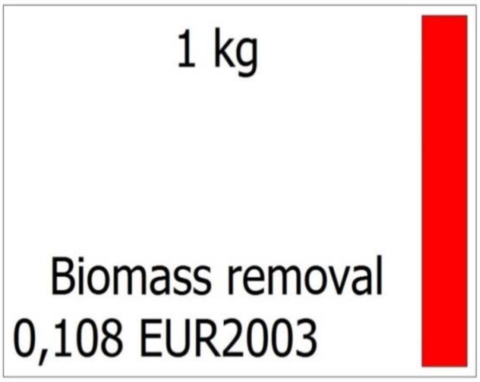
Source: Modeling in SimaPRO.

Appendix 6: Products' network of CoNG$_{me1}$



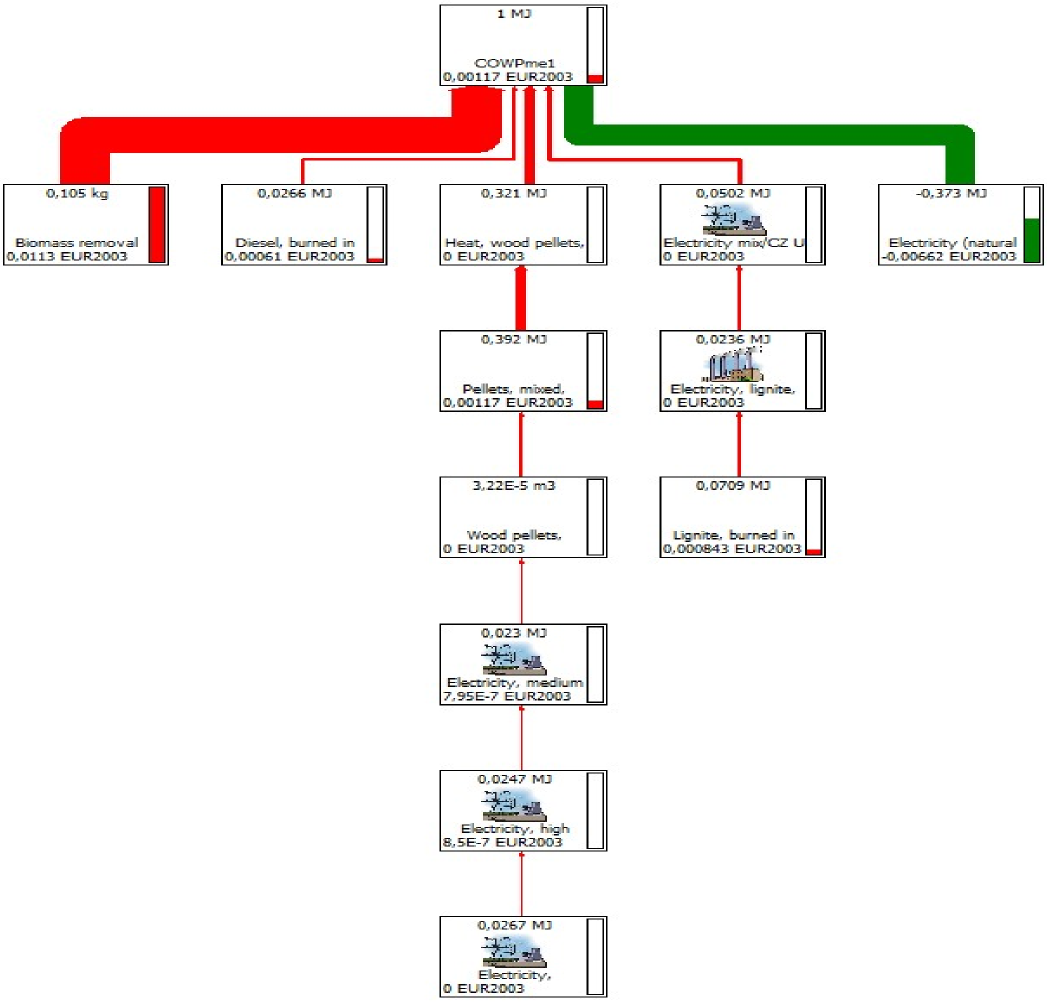
Source: Modeling in SimaPRO.

Appendix 7: Products' Networks for Wood residue removal



Source: Modeling in SimaPRO.

Appendix 8: Products' Networks for CoWP$_{me1}$



Source: Modeling in SimaPRO.

Appendix 9: Detail environmental performances per 1 MJ of district heat production (CoNG$_{me1}$)

	GWP	AP	EP, aquatic	EP, terrestrial	NRE Use
Processes/Impact	kg CO_2-eq	m^2 UES	kg NO_3-eq	m^2 UES	MJ-primary
Upstream	**8.28E-03**	**2.39E-04**	**1.95E-06**	**8.25E-04**	**3.32E+00**
extraction and transportation	8.28E-03	2.39E-04	1.95E-06	8.25E-04	3.32E+00
Downstream	**3.14E-02**	**-3.94E-05**	**-1.74E-06**	**-1.37E-05**	**-8.16E-01**
Combustion	9.39E-02	5.49E-04	5.83E-06	2.75E-03	0.00E+00
water, decarbonised at plant	2.59E-06	1.08E-07	5.70E-10	1.89E-07	2.89E-05
water, softening at plant	2.44E-07	1.07E-08	5.27E-11	1.79E-08	2.82E-06
Co-product	-6.25E-02	-5.89E-04	-7.57E-06	-2.76E-03	-8.16E-01
Disposal, residues	3.15E-08	4.88E-09	1.23E-11	5.57E-09	5.36E-07
Net Impact	**3.97E-02**	**2.00E-04**	**2.17E-07**	**8.11E-04**	**2.5E+00**

Appendix 10: Detail environmental performances per 1 MJ of district heat production (CoNG$_{me2}$)

	GWP	AP	EP, aquatic	EP, terrestrial	NRE Use
Processes/Impact	kg CO_2-eq	m^2 UES	kg NO_3-eq	m^2 UES	MJ-primary
Upstream	**8.28E-03**	**2.39E-04**	**1.95E-06**	**8.25E-04**	**3.32E+00**
extraction and transportation	8.28E-03	2.39E-04	1.95E-06	8.25E-04	3.32E+00
Downstream	**-9.69E-03**	**-2.21E-03**	**-3.31E-06**	**-6.69E-04**	**-1.21E+00**
Combustion	9.39E-02	5.49E-04	5.83E-06	2.75E-03	0.00E+00
water, decarbonised at plant	2.59E-06	1.08E-07	5.70E-10	1.89E-07	2.89E-05
water, softening at plant	2.44E-07	1.07E-08	5.27E-11	1.79E-08	2.82E-06
Co-product	-1.04E-01	-2.76E-03	-9.15E-06	-3.42E-03	-1.21E+00
Disposal, residues	3.15E-08	4.88E-09	1.23E-11	5.57E-09	5.36E-07
Net Impact	**-1.41E-03**	**-1.97E-03**	**-1.36E-06**	**1.56E-04**	**2.1E+00**

Appendix 11: Detail environmental performances per 1 MJ of district heat production (CoNG$_{me3}$)

	GWP	AP	EP, aquatic	EP, terrestrial	NRE Use
Processes/Impact	kg CO_2-eq	m^2 UES	kg NO_3-eq	m^2 UES	MJ-primary
Upstream	**8.28E-03**	**2.39E-04**	**1.95E-06**	**8.25E-04**	**3.32E+00**
extraction and transportation	8.28E-03	2.39E-04	1.95E-06	8.25E-04	3.32E+00
Downstream	**9.28E-02**	**4.66E-04**	**5.04E-06**	**2.67E-03**	**-1.64E-02**
Combustion	9.39E-02	5.49E-04	5.83E-06	2.75E-03	0.00E+00
water, decarbonised at plant	2.59E-06	1.08E-07	5.70E-10	1.89E-07	2.89E-05
water, softening at plant	2.44E-07	1.07E-08	5.27E-11	1.79E-08	2.82E-06
Co-product	-1.08E-03	-8.33E-05	-7.91E-07	-8.29E-05	-1.64E-02
Disposal, residues	3.15E-08	4.88E-09	1.23E-11	5.57E-09	5.36E-07
Net Impact	**1.01E-01**	**7.06E-04**	**7.00E-06**	**3.49E-03**	**3.3E+00**

Appendix 12: Detail environmental performances per 1 MJ of district heat production (CoWS$_{me1}$)

	GWP	AP	EP, aquatic	EP, terrestrial	NRE Use
	kg CO_2-eq	m^2 UES	kg NO_3-eq	m^2 UES	MJ-primary
Upstream	**2.49E-02**	**6.41E-04**	**1.25E-04**	**1.95E-03**	**8.32E-02**
Straw removal	2.15E-02	4.52E-04	1.24E-04	1.33E-03	2.94E-02
Collection and pre-processing	3.34E-03	1.89E-04	1.47E-06	6.18E-04	5.38E-02
Baling, handling	*8.88E-04*	*7.83E-05*	*7.77E-07*	*3.19E-04*	*1.17E-02*
transportation	*2.45E-03*	*1.11E-04*	*6.92E-07*	*2.98E-04*	*4.20E-02*
Downstream	**-6.69E-02**	**9.57E-03**	**1.48E-06**	**4.28E-03**	**-8.81E-01**
Chopping	8.59E-05	8.71E-06	6.88E-08	3.16E-05	1.34E-03
Combustion	7.06E-04	1.02E-02	1.53E-05	7.20E-03	0.00E+00
Co-product	-6.78E-02	-6.46E-04	-1.41E-05	-3.00E-03	-8.86E-01
electricity (displaced)	*-6.78E-02*	*-6.38E-04*	*-8.21E-06*	*-3.00E-03*	*-8.85E-01*
Slag (nutrient values displaced)	*-3.77E-05*	*-7.60E-06*	*-5.94E-06*	*-4.36E-06*	*-6.43E-04*
Transportation of slag	1.65E-04	1.23E-05	1.00E-07	4.53E-05	2.78E-03
Disposal of fly ash	1.73E-05	2.60E-06	1.77E-07	3.26E-06	3.19E-04
Gross Impact	**2.59E-02**	**1.09E-02**	**1.41E-04**	**9.23E-03**	**8.77E-02**
Net Impact	**-4.20E-02**	**1.02E-02**	**1.25E-04**	**6.23E-03**	**-7.98E-01**

Appendix 13: Detail environmental performances per 1 MJ of district heat production (CoWS$_{me2}$)

	GWP	AP	EP, aquatic	EP, terrestrial	NRE Use
	kg CO_2-eq	m^2 UES	kg NO_3-eq	m^2 UES	MJ-primary
Upstream	**2.49E-02**	**6.41E-04**	**1.25E-04**	**1.95E-03**	**8.32E-02**
Straw removal	2.15E-02	4.52E-04	1.24E-04	1.33E-03	2.94E-02
Collection and pre-processing	3.34E-03	1.89E-04	1.47E-06	6.18E-04	5.38E-02
Baling, handling	*8.88E-04*	*7.83E-05*	*7.77E-07*	*3.19E-04*	*1.17E-02*
transportation	*2.45E-03*	*1.11E-04*	*6.92E-07*	*2.98E-04*	*4.20E-02*
Downstream	**-1.11E-01**	**7.22E-03**	**-2.30E-07**	**3.57E-03**	**-1.31E+00**
Chopping	8.59E-05	8.71E-06	6.88E-08	3.16E-05	1.34E-03
Combustion	7.06E-04	1.02E-02	1.53E-05	7.20E-03	0.00E+00
Co-product	-1.12E-01	-3.00E-03	-1.59E-05	-3.71E-03	-1.32E+00
electricity (displaced)	*-1.12E-01*	*-2.99E-03*	*-9.92E-06*	*-3.71E-03*	*-1.32E+00*
Slag (nutrient values displaced)	*-3.77E-05*	*-7.60E-06*	*-5.94E-06*	*-4.36E-06*	*-6.43E-04*
Transportation of slag	1.65E-04	1.23E-05	1.00E-07	4.53E-05	2.78E-03
Disposal of fly ash	**1.73E-05**	**2.60E-06**	**1.77E-07**	**3.26E-06**	**3.19E-04**
Gross Impact	**2.59E-02**	**1.09E-02**	**1.41E-04**	**0.009**	**8.77E-02**
Net Impact	**-0.087**	**0.008**	**1.25E-04**	**0.006**	**-1.230**

Appendix 14: Detail environmental performances per 1 MJ of district heat production (CoWS$_{me3}$)

	GWP	AP	EP, aquatic	EP, terrestrial	NRE Use
	kg CO_2-eq	m^2 UES	kg NO_3-eq	m^2 UES	MJ-primary
Upstream	**2.49E-02**	**6.41E-04**	**1.25E-04**	**1.95E-03**	**8.32E-02**
Straw removal	2.16E-02	4.52E-04	1.24E-04	1.33E-03	2.95E-02
Collection and pre-processing	3.34E-03	1.89E-04	1.47E-06	6.18E-04	5.38E-02
Baling, handling	*8.88E-04*	*7.83E-05*	*7.77E-07*	*3.19E-04*	*1.17E-02*
transportation	*2.45E-03*	*1.11E-04*	*6.92E-07*	*2.98E-04*	*4.20E-02*
Downstream	**-2.31E-04**	**1.01E-02**	**8.83E-06**	**7.19E-03**	**-1.40E-02**
Chopping	8.59E-05	8.71E-06	6.88E-08	3.16E-05	1.34E-03
Combustion	7.06E-04	1.02E-02	1.53E-05	7.20E-03	0.00E+00
Co-product	-1.21E-03	-9.79E-05	-6.79E-06	-9.43E-05	-1.85E-02
electricity (displaced)	*-1.17E-03*	*-9.03E-05*	*-8.58E-07*	*-9.00E-05*	*-1.78E-02*
Slag (nutrient values displaced)	*-3.77E-05*	*-7.60E-06*	*-5.94E-06*	*-4.36E-06*	*-6.43E-04*
Transportation of slag	1.65E-04	1.23E-05	1.00E-07	4.53E-05	2.78E-03
Disposal of fly ash	1.73E-05	2.60E-06	1.77E-07	3.26E-06	3.19E-04
Gross Impact	**2.59E-02**	**1.09E-02**	**1.41E-04**	**9.23E-03**	**8.77E-02**
Net Impact	**2.47E-02**	**1.08E-02**	**1.34E-04**	**9.14E-03**	**6.92E-02**

Appendix 15: Detail environmental performances per 1 MJ of district heat production ($CoWP_{me1}$)

	GWP	AP	EP, aquatic	EP, terrestrial	NRE Use
	kg CO_2-eq	m^2 UES	kg NO_3-eq	m^2 UES	MJ-primary
Upstream	**1.59E-01**	**1.83E-03**	**8.13E-06**	**3.66E-03**	**3.53E-01**
Wood residue removal	1.36E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Collection and pre-processing	2.23E-02	1.83E-03	8.13E-06	3.66E-03	3.53E-01
Mechanical energy	*2.21E-03*	*2.29E-04*	*1.86E-06*	*8.58E-04*	*3.32E-02*
Heat for drying	*4.97E-03*	*5.65E-04*	*3.20E-06*	*1.46E-03*	*9.56E-02*
electricity for drying	*1.11E-02*	*6.13E-04*	*1.36E-06*	*5.82E-04*	*1.58E-01*
Transport, freight	*8.63E-04*	*2.85E-04*	*8.45E-07*	*3.91E-04*	*1.35E-02*
Transport, local	*3.19E-03*	*1.38E-04*	*8.59E-07*	*3.70E-04*	*5.28E-02*
Downstream	**-6.73E-02**	**2.97E-04**	**-1.76E-07**	**7.97E-04**	**-8.85E-01**
Combustion	4.85E-04	9.35E-04	8.04E-06	3.79E-03	0.00E+00
Co-product	-6.78E-02	-6.39E-04	-8.24E-06	-3.00E-03	-8.85E-01
electricity (displaced)	*-6.78E-02*	*-6.38E-04*	*-8.21E-06*	*-3.00E-03*	*-8.85E-01*
Slag (nutrient values displaced)	*-1.62E-07*	*-3.26E-08*	*-2.55E-08*	*-1.87E-08*	*-2.75E-06*
Transportation of slag	1.09E-05	8.11E-07	6.60E-09	2.99E-06	1.83E-04
Disposal of fly ash	1.20E-06	1.79E-07	1.22E-08	2.25E-07	2.20E-05
Gross Impact	**1.59E-01**	**2.77E-03**	**1.62E-05**	**7.46E-03**	**3.54E-01**
Net Impact	**9.14E-02**	**2.13E-03**	**7.96E-06**	**4.46E-03**	**-5.31E-01**

Appendix 16: Detail environmental performances per 1 MJ of district heat production ($CoWP_{me2}$)

	GWP	AP	EP, aquatic	EP, terrestrial	NRE Use
	kg CO_2-eq	m^2 UES	kg NO_3-eq	m^2 UES	MJ-primary
Upstream	**1.59E-01**	**1.87E-03**	**8.30E-06**	**3.74E-03**	**3.60E-01**
Wood residue removal	1.36E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Collection and pre-processing	2.27E-02	1.87E-03	8.30E-06	3.74E-03	3.60E-01
Mechanical energy	*2.21E-03*	*2.29E-04*	*1.86E-06*	*8.58E-04*	*3.32E-02*
Heat for drying	*4.97E-03*	*5.65E-04*	*3.20E-06*	*1.46E-03*	*9.56E-02*
electricity for drying	*1.11E-02*	*6.13E-04*	*1.36E-06*	*5.82E-04*	*1.58E-01*
Transport, freight	*9.53E-04*	*3.15E-04*	*9.33E-07*	*4.32E-04*	*1.49E-02*
Transport, local	*3.50E-03*	*1.52E-04*	*9.42E-07*	*4.06E-04*	*5.79E-02*
Downstream	**-1.12E-01**	**-2.06E-03**	**-1.89E-06**	**8.58E-05**	**-1.32E+00**
Combustion	4.84E-04	9.35E-04	8.04E-06	3.79E-03	0.00E+00
Co-product	-1.12E-01	-2.99E-03	-9.95E-06	-3.71E-03	-1.32E+00
electricity (displaced)	*-1.12E-01*	*-2.99E-03*	*-9.92E-06*	*-3.71E-03*	*-1.32E+00*
Slag (nutrient values displaced)	*-1.62E-07*	*-3.26E-08*	*-2.55E-08*	*-1.87E-08*	*-2.75E-06*
Transportation of slag	1.09E-05	8.11E-07	6.60E-09	2.99E-06	1.83E-04
Disposal of fly ash	1.20E-06	1.79E-07	1.22E-08	2.25E-07	2.20E-05
Gross Impact	**1.60E-01**	**2.81E-03**	**1.64E-05**	**7.53E-03**	**3.60E-01**
Net Impact	**4.73E-02**	**-1.82E-04**	**6.42E-06**	**3.82E-03**	**-9.57E-01**

Appendix 17: Detail environmental performances per 1 MJ of district heat production (CoWP$_{me3}$)

	GWP	AP	EP, aquatic	EP, terrestrial	NRE Use
	kg CO_2-eq	m^2 UES	kg NO_3-eq	m^2 UES	MJ-primary
Upstream	**1.59E-01**	**1.87E-03**	**8.30E-06**	**3.74E-03**	**3.60E-01**
Wood residue removal	1.36E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Collection and pre-processing	2.27E-02	1.87E-03	8.30E-06	3.74E-03	3.60E-01
Mechanical energy	*2.21E-03*	*2.29E-04*	*1.86E-06*	*8.58E-04*	*3.32E-02*
Heat for drying	*4.97E-03*	*5.65E-04*	*3.20E-06*	*1.46E-03*	*9.56E-02*
electricity for drying	*1.11E-02*	*6.13E-04*	*1.36E-06*	*5.82E-04*	*1.58E-01*
Transport, freight	*9.53E-04*	*3.15E-04*	*9.33E-07*	*4.32E-04*	*1.49E-02*
Transport, local	*3.50E-03*	*1.52E-04*	*9.42E-07*	*4.06E-04*	*5.79E-02*
Downstream	**-6.71E-04**	**8.45E-04**	**7.18E-06**	**3.70E-03**	**-1.76E-02**
Combustion	4.84E-04	9.35E-04	8.04E-06	3.79E-03	0.00E+00
Co-product	-1.17E-03	-9.03E-05	-8.84E-07	-9.00E-05	-1.78E-02
electricity (displaced)	*-1.17E-03*	*-9.03E-05*	*-8.58E-07*	*-9.00E-05*	*-1.78E-02*
Slag (nutrient values displaced)	*-1.62E-07*	*-3.26E-08*	*-2.55E-08*	*-1.87E-08*	*-2.75E-06*
Transportation of slag	1.09E-05	8.11E-07	6.60E-09	2.99E-06	1.83E-04
Disposal of fly ash	1.20E-06	1.79E-07	1.22E-08	2.25E-07	2.20E-05
Gross Impact	**1.60E-01**	**2.81E-03**	**1.64E-05**	**7.53E-03**	**3.60E-01**
Net Impact	**1.58E-01**	**2.72E-03**	**1.55E-05**	**7.44E-03**	**3.42E-01**

Appendix 18: *Article-I-* Life Cycle Assessment of District heat production in a straw fired cogeneration unit and comparison with a boiler.

Life Cycle Assessment of District heat production in a straw fired cogeneration unit and comparison with a boiler

Article-I: Draft version

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Abstract:

This article deals with the Life Cycle Assessment (LCA) of wheat straw as a fuel alternative to produce district heat in a Combined Heat and Power (CHP) plant and compares with the combustion of the same fuel in a boiler producing heat only. The article also compares environmental performances of straw-with natural gas for the same purpose. Environmental impact categories for the assessment are Global-warming potential (GWP) 100 years, acidification potential (AP), aquatic and terrestrial eutrophication potential (EP) and non-renewable energy (NRE) use. We have found that the straw-fired CHP plant leads to GWP of -86.54 g CO_2-eq/MJ heat, AP of 0.008 m^2 UES/MJ heat, aquatic and terrestrial EP of 0.471 g NO_3-eq/J heat, and 0.006 m^2 UES/MJ heat respectively, and NRE use of -1.23 MJ primary/MJ heat. Straw fired in a CHP plant instead of in a boiler possess better environmental performances in all impact categories. Nevertheless, straw possess higher EP and AP when compared to natural gas, but from the standpoint of lower GWP and NRE use shows better performances.

1. Introduction

Manure, grass and lignocellulosic biomass (wood and straw) are amongst the popular sources of biomass in European Union, including Denmark (Tonini and Astrup 2012). Denmark is the pioneer country to use straw as a fuel source in the EU, which is because of its dedicated policies, since back from the first oil crisis of 1973 (Skøtt and BioPress 2011; Parajuli 2012), and nowadays Denmark uses approximately 1.8 Mt of straw each year for energy (Giuntoli et al. 2012). Compared to other biomass sources some of the strong advantages of wheat straw includes: its minimum competition with food and feed industries, and associated land use change issues (Fan et al. 2006), and thus food ethics issues. The agricultural statistics of Denmark shows that of the total area covered by cereals, i.e. 1484 (‘000 ha) in the year 2011, the area covered by wheat was about 50%. Similarly, the total straw production was from the area of 996 (’000 ha), with a productivity of about 3.29 t/ha of the straw production area (Statistics Denmark 2012). This reveals that in the course of diversifying the renewable energy mix for sustainable energy supply in Denmark, straw could play a significant role. In general, Denmark only has limited available renewable energy sources, of which one of the most important – wind power– inherently is of a fluctuating nature (Lund and Münster 2003; Lund 2005) and thus needs to be supplemented by fuel-based technologies (Hvelplund et al. 2011). At the meantime while integrating wind power in a larger scale to satisfy the higher penetration of renewable energy in Denmark, it is also necessary to address the underlying issues in relation to the demand side management (Lund 2005), and in particular about the management of the existing operations of CHP and heat productions. Biomasses including straw is thus important in the course of the Danish renewable energy plans envisioned for the year 2020 and 2030, and most importantly in the context of its 100% renewable energy strategy to be met by the year 2050. The analysis of the Danish Ministry of Climate and energy (www.ens.dk 2011), as well as in independent analyses from the Danish Society of Engineers (IDA 2009) and in studies including (Østergaard et al. 2010; Østergaard and Lund 2011; Kwon and Østergaard 2012) stressed about the prudent utilisation of this finite resource.

In spite of wheat straw possessing a number of advantages compared to other biomass, particularly from the perspectives of minimizing the potential occupancy of additional land compared to the alternative of cultivating other biomass (such as grasses), there are some debates on the alternative means of straw utilisation. Debates are particularly anchored with environmental impacts reported due to the crop residue removal from agricultural cropping systems for bioenergy production (Dick et al. 1998; Clapp et al. 2000; Lal 2008). These includes N_2O soil emissions, leaching of nitrate, and changes in soil carbon pools (Dick et al. 1998) and on limiting the availability of nutrients from straw to soil (Christensen and Olesen 1998). In order to have a proper basis for decision-making on the large-scale use of wheat straw for energy purposes, it is thus important addressing the entire sets of impacts from the utilisation as well as the from the alternative fuels.

In this article, Denmark is considered as the geographical boundary for the assessment of environmental performances in relation to the straw utilisation in the production of district heat. Wheat straw is selected because it is the most common crop and the most important source for both grain and straw in Denmark (Statistics Denmark 2010). District heating is selected as an end-use because power and heat production is one of the important sectors that need to be optimised for fulfilling future sustainable energy goals of the country. Furthermore, biomass (particularly straw) is regarded as a realistic fuel in this sector (Mathiesen et al. 2011). LCA of the straw as a fuel input is carried out in two different types of combustion system, which are Combined Heat and Power (CHP) and a boiler. The former system produces both heat and electricity simultaneously, and the latter produces only heat.

Section 2 of this article presents the materials and methods–notably the basic LCA and materials characteristics as well as the system boundary and other assumptions. Section 3 present the LCA analyses of the present case, and in section 4 reviews on probable solutions to the identified environmental issues in relation to the scope of this study are presented. Finally main conclusions are drawn in Section 5.

2. Material and Methods

2.1. Scope and Functional Unit

The scope of this study is to assess the life cycle impacts of district heat production with straw as a fuel input in a CHP plant and compare with a boiler. The study also further aims to compare the district heat production based on natural gas fired in the CHP. The functional unit of the life cycle assessment (LCA) is 1 MJ of heat production and the impact categories are: GWP, NRE use, AP, and EP (terrestrial and aquatic).

2.2. System boundary, Process Descriptions and basic assumptions

The system boundary (Figure 1) comprises of energy conversion stages: straw removal, collection and pre-processing, combustion, and management of fly ash and bottom ash (slag) both for CHP and boiler. We have assumed heat is the main product and electricity as a co-product of the CHP plant, as electricity is sold as additional product while simultaneously producing heat and electricity, particularly in northern and western European countries (Lund and Andersen 2005; Rasburskis et al. 2006). Other output of the system are bottom ash (slag) and fly ash, the former is considered to be reused as fertilisers because of its nutrient content, and the latter is realized to be disposed in a landfill sites because of the presence of heavy metals in the fly ash (Cenni et al. 2001; Pöykiö et al. 2009). The processes involved in the energy conversion processes and basic assumptions employed in this study are discussed in the section 2.2.1-2.2.3. .

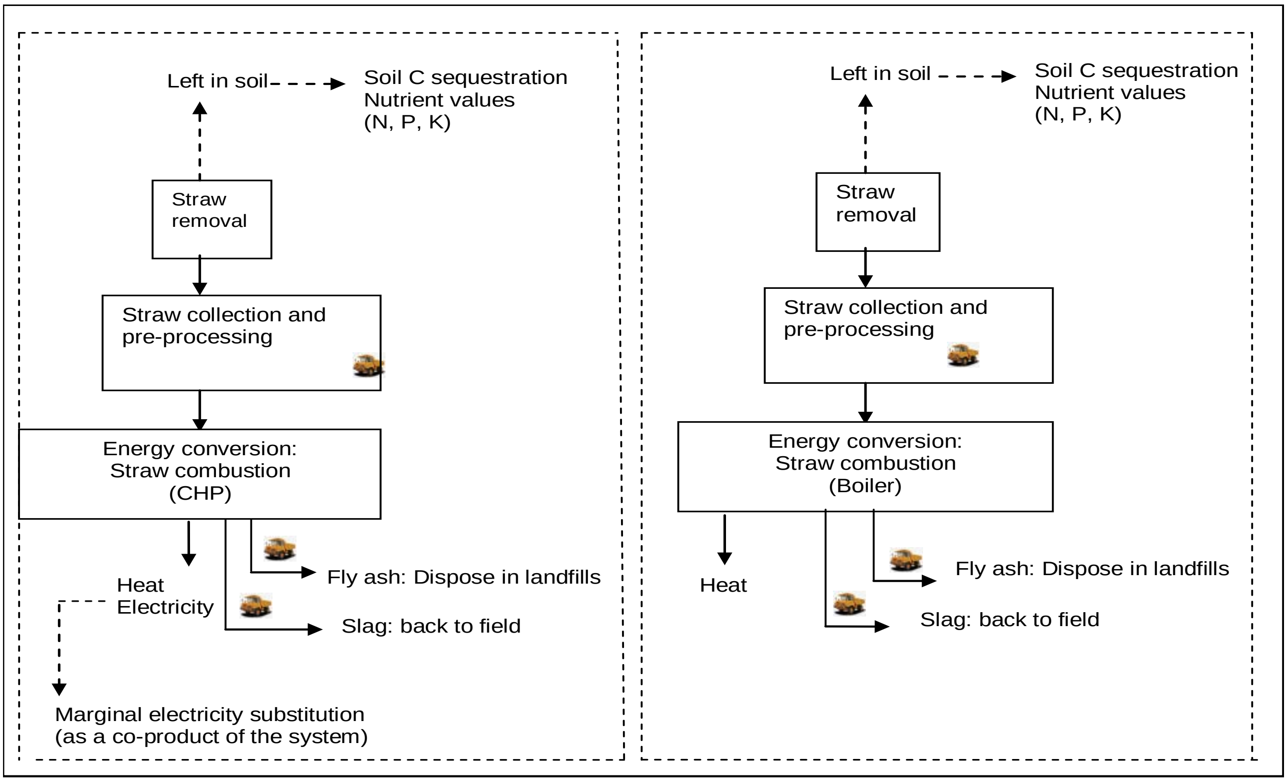


Figure 1: System Boundary the reference flow of Wheat straw (CHP and Boiler)

2.2.1. Straw removal

Before starting with the identifications of issues within the straw removal process, and establish its connection as an alternative fuel in the energy market, we have tried to answer following questions;

i. How the removal of straw limit the soil C sequestration potential compared to the situation if alternatively the straw is ploughed back into the field in the next cropping cycle?
ii. How it will have an impact on the availability of soil nutrients, and in turn what are the consequences associated with it?

The above mentioned first query is about assessing the GWP, which would have been avoided due to soil C sequestration if the straw is not removed from the field (Powlson et al. 2011). For this we have also reviewed about the process of soil C buildup and time based soil C pool changes, after the application of crop residues or manures. Petersen et al. () have argued about the emission reduction in different time series. For 20-years, the soil C build-up is 19.8 % and 21.3 % of the total C content in the crop residue for loamy sand and sandy loam soil respectively of Denmark. Likewise, 8.8% and 9.7% of the total C content in the crop residue for the respective soil types in 100 years' time frame (Petersen and Knudsen 2010).

In this article, we have assumed that the 100-years soil C sequestration potential of the straw is 88 kg C (i.e. 8.8%) per total C content in the dry matter (DM) of the straw (Petersen and Knudsen 2010). The C content of the straw is assumed at 45.3% per t DM (Møller et al. 2005). Hence, 1 t (85% DM) straw leads to soil C sequestration potential of 38.38 kg C, which is avoided along the removed straw leads and thus contributes to increase the GWP compared to the situation if turned back to the soil. In addition to this, the straw removal is also associated with organic nitrogen content, which is assumed to be buildup at a C:N ratio of 1:10 (Petersen and Berntsen 2003). The soil N-build up over a 20-year time frame is 4.3 kg, whereas in 100-years it is 3.23 kg, and hence removal of the straw also limits this process, since availability of this nutrient is dependent with the Soil C sequestration. However its availability also leads to changes in the leaching of nitrate to the aquatic ecosystem. We have considered these effects, while discussing about the consequences of the straw removal (Table 2).

The second question on the straw removal is associated with the constraining the soil nutrients availability from the straw. It has been argued that if straw is removed from the agricultural field, compensation of the equivalent amount of fertilisers should be made (Nguyen et al. 2013; Schmidt and Brandao 2013). We have estimated this equivalent amount of fertilisers from the elemental composition of the straw, Nitrogen (N), Phosporous (P) and Potassium (K) values of the straw (Møller et al. 2005). We have further assumed that about 30% of the N in straw is available to crop as N is immobilized instead of being mineralised at least for first few years (Nguyen et al. 2013). Whilst, we have assumed that 100% of the fertiliser value available in the form of P and K in the straw is available to the crop (Nguyen et al. 2013). The P and K values are further transformed to P_2O_5 and K_2O, by factoring with the ratio of their molecular weight. Cherubini and Strømman (2011) reported that the application of fertilisers leads to nitrate leaching, hence if a compensation is made on the amount of fertilisers it is also necessary to estimate the equivalent amount of direct and indirect emissions related to fertiliser application. Nitrate leaching is estimated considering the amount of nitrogeneous fertiliser applied during the compensation of nutrients and is estimated based on IPCC (2006). Table 2 shows the detail steps in relation to estimating the direct and indirect emissions associated with the straw removal process. .

2.2.2. Collection and Pre-processing

Fuel inputs for the processes such as baling and handling of biomass are estimated based on the study Dalgaard et al. (2001). This stage of the energy conversion of the straw also includes the transportation of the biomass at a distance of 200 km to deliver the biomass at the power plant.

2.2.3. Heat Production and waste management

At first, the gross district heat output is estimated in relation to the reference flow of feedstock (i.e. 1 t, 85% DM of the straw. The thermal and electrical efficiencies of the CHP plant is assumed as 60% and 25% respectively (www.videncenter.dk 2004; energinet.dk 2012). Similarly, the thermal efficiency of boiler is 85% (videncenter.dk 1998). These efficiencies are relatively modest compared to units operated on fossil fuels due to the corrosiveness of combusting straw at high temperatures. Electricity and heat required during the combustion process are assumed to be 40 MJ and 110 kWh respectively per t (85% DM) as reported in Nielsen (2004). It is assumed that both heat and electricity required for the combustion are utilised from the produced power of the straw fired CHP. Emissions from the combustion of the feedstock is based on Nielsen (2004). Despite there are other emissions in relation to the combustion of the straw, we have not considered all of them, considering the scope and the impact categories as discussed in section 2.1.

Net heat output is estimated by subtracting the heat input required in the combustion process from the gross value, and thus the net fuel input is also re-calculated. The net electricity output is estimated accordingly, considering the electricity input required during the combustion process in the case of CHP, whereas in the case of boiler it is assumed to be externally source and is from the Danish electricity mix. The data base of this electricity mix is based on Ecoinvent Centre (2010).

The total amount of bottom ash/slag produced from the combustion process is assumed to be 54 kg tDM^{-1} (Nielsen 2004). Nutrient values of the slag are estimated considering the average weight of P and K content in it, which are 1.45% and 16% respectively (videncenter.dk 1998) (Table 1). 100 % of the nutrient values present in the slag is assumed to be collected (Nguyen et al. 2013). We have not accounted the N content of the bottom ash, as most of the Nitrogen is lost in the combustion process (Nguyen et al. 2013). The nutrients values (P and K) available in the bottom ash are assumed to displace the equivalent amount of fertiliser (P and K fertiliser values). This displacement of the fertiliser thus consequently displaces the associated environmental impact of producing them. Transportation distance of the bottom to deliver for applying in the agricultural field is considered similar to that of the distance of transporting the dried biomass (i.e. 200 km). Similarly, Fly ash (deposit) is assumed to be 8.3 kg per t (85% DM) of the residue (Nielsen 2004) and disposed in a landfill sites.

2.3. Life Cycle Inventory and LCA Methods

Life Cycle Inventory (LCI) in the energy conversion process of straw, finally to produce heat in a CHP and boiler is depicted in Table 1. We have adopted the system expansion approach to assess the environmental performances in relation to 1 MJ heat production, where we have looked into the effects and influences of a particular product in the overall system. For instance impact of co-produced electricity and nutrient values of slag in the overall life cycle process of district heat production. Hence, influences of such product(s) could play a significant role in displacing the environmental impacts of similar kind of product available in the market. In our case the co-produced electricity from a CHP displaces the marginal electricity and their associated environmental impacts, which on other hand is not possible in the boiler. Some of the rationality of this approach include: benefits to assess the changes in the environmental consequences with the changes in the demand of the marginal product (Dalgaard et al. 2008), and also when the production efficiency changes. Likewise, Schmidt (2008) highlighted that this approach is useful to assess and compare the environmental consequences between two situations of the material flow, such as; ‘a product being at a place’ and ‘product being removed’.

We have used the “Stepwise2006”method (2.0 LCA consultant 2012) to assess the environmental impacts for the impact categories as discussed in Section 2.1. 100-years GWP factors of methane (CH_4), and di-nitrogen monoxide (N_2O) found in the ‘Stepwise 2006 method’ are adjusted to 25 and 298 respectively as per IPCC (2007). It is also assumed that the EP (aquatic) has an impact on the lake ecosystem, since historically Danish lakes are regarded highly eutrophic (Yang et al. 2008).

Table 1: LCI of district heat production based on straw fired CHP plant

Process	Unit	Amount	Comments/Remarks	LCI data
Collection and pre-processing				
Inputs				
Amount of straw	t	1		
Baling and Handling[1]	MJ	61	Based on Dalgaard et al. (2001)	
Chopping straw at power plant[2]	MJ	6.46	Based on Nielsen (2004).	
Transport (to power plant)	tkm	170	0.85 tDM * 200km (Lorry (>32 t)	(Ecoinvent Centre 2010)
Outputs	t	1	1 t (85% DM) at Power plant	
Combustion (1 t, 85% DM)				
Inputs				
Straw, 85% DM	t	1	LHV=14.5 GJ/t	
Heat (own product)[3]	MJ	40	Assumed to be used from the system.	
Electricity[3]	kWh	110	CHP: Electricity is used from the system and Boiler : assumed to be externally feed-in.	
Outputs (CHP)				
Heat	MJ	8700	Net heat output[3] = gross heat output-heat	
Net heat output	MJ	8660		
Electricity	kWh	1006	Net electricity output[3] = gross electricity output-electricity input	
Net electricity output	kWh	897		
Outputs (Boiler)				
Heat	MJ	12325	Net heat output[3] = gross heat output-heat input	
Net heat output	MJ	12285		
Net straw input				
CHP	t	0.995	Estimated based on the net heat output	
Boiler	t	0.996		
Bottom ash (slag) recycling[4]			86% of the bottom ash collectable (Nguyen et al. 2013)	
CHP	kg	53.73		
Boiler	kg	53.78		
Transport to proper sites, by truck				
CHP	tkm	10.74	Lorry (>16 ton) for 200 km	(Ecoinvent Centre 2010)
Boiler	tkm	10.75		
Nutrient[5]			Fertiliser value	
CHP				(Ecoinvent Centre 2010)
P fertilizer value	kg	0.779		
K fertilizer value	kg	8.59		
Boiler				
P fertilizer value	kg	0.779		
K fertilizer value	kg	8.60		
Fly ash disposal in landfills			Estimated based on the fly ash deposits per tDM (Nielsen 2004)	(Ecoinvent Centre 2010)
CHP	kg	8.25		
Boiler	kg	8.26		

Direct emissions (fuel input)[6] (g)	g		Total emissions calculated based on heat content of net fuel input for the CHP and boiler
CHP			
CH_4		7.21	
N_2O		20.2	
SO_2		677.74	
NOx		1889	
HCl		663.32	

Assumptions:

[1] estimated diesel consumption for baling and handling = 2 lt^{-1} (Dalgaard et al. 2001). LHV of diesel =35.9 MJl^{-1}.

[2] estimated diesel consumption for chopping 1 t of straw = 0.18 l.

[3] heat and electricity required during combustion process per tDM (Nielsen 2004). Electricity input from the 'electricity mix DK/U' in case of the boiler (Ecoinvent Centre 2010).

[4] bottom ash per 1 tDM of wheat straw =54 kg (Nielsen 2004)

[5] nutrient Value =Total bottom ash* P and K content in the ash.

[6] emissions from the combustion of wheat straw based on Nielsen and Illerup (2003) and Nielsen (2004). Net fuel input in CHP is 14.42 GJ. For boiler estimated accordingly with net fuel input equivalent to 14.44 GJ. Other emissions are not discussed considering the impact categories selected for this study.

3. Results and Discussions

3.1. Consequence of the straw removal

Table 2 shows the consequences of the removal of 1 t (85% DM) of the straw from the agricultural field, where it relates with impacts such as constraining the Soil C sequestration potential and associated N-buildup from the biomass decay process, which could have been possible if the straw is alternatively left in the field. It also relates about limiting the opportunity of gaining soil nutrients from the straw if instead ploughed back into the field. Consequences of the straw removal are further summarized as follows;

- Limits the soil C sequestration potential at the rate of 38.38 kg per 1 t of straw (85% DM) in a 100-year time frame
- Compensation of fertilisers is required to fulfill the soil nutrients removed along with the straw. The nutrient values of the straw, which are removed along with the straw is estimated at 1.53, 0.765 and 12.75 kg (N, P, K) per t (85% DM) of the straw.
- Emissions from the fertiliser applications, primarily from the manufacturing process of compensating amount of fertilisers are the added impact due to the removal process.

In addition to the above mentioned consequences, other important impacts are direct and in-direct N_2O emissions. For e.g. 0.0153 kg of N_2O-N is the emission from the application of N fertilisers to compensate the nutrient loss. Likewise, in-direct N_2O-N is 0.032 kg per 1 t (85% DM) of the straw removed (Table 2). Since removal of straw corresponds to limiting the soil C sequestration, it also limits the soil N-build up and reduces the eutrophication (aquatic) at the rate of -0.06 Kg NO_3-N per t (85%DM) of straw.

In relation to the life cycle impact considering above mentioned effects, removal of 1 t (85% DM) of the straw corresponds to increase the GWP by 135.5 kg CO_2eq, acidification potential 2.8 m^2UES, EP (aquatic) 0.8 kg NO_3eq, EP (terrestrial) 8.4 m^2UES and NRE use at 185 MJ-primary (Table 2).

Table 2: Environmental consequences of straw removal

	Unit	Amount	Comments
Reference Flow	t	1	1 t (85% DM)
Soil C sequestration loss, 100 years perspectives. (kg CO_2-eq)	Kg	141	Based on elemental composition of the straw[1]. 8.8% of C content in the straw (100 years)[2]
Additional Fertiliser inputs			
Calcium Ammonium Nitrate	Kg	1.53	Estimated N value[3] = 1.53 kg
Triple superphosphate (P_2O_5)	Kg	1.75	Estimated P value[4] = 0.765 kg
Potassium Chloride (K_2O)	Kg	7.36	Estimated K value[5] = 12.75 kg
Emissions			
N_2O-N from extra N application as a fertilizer	Kg	0.0153	0.01* kg N in fertilizer (IPCC 2006)
Avoided N_2O-N from crop residues	Kg	- 0.051	0.01*kg N in crop residues[2] (IPCC 2006).
NH_3-N from added fertiliser-N application	Kg	0.0306	0.02*kg N in fertilizer (Nemecek and Kägi 2007)
NO-N from additional fertiliser-N application	Kg	0.0107	0.007*kg N in fertilizer (Nguyen et al. 2010)
N_2-N from additional fertiliser-N application	Kg	0.0719	0.047*kg N in fertilizer (Nguyen et al. 2010)
NO_3-N from additional fertiliser (potential changes in the leaching due to straw removal)[6]	Kg	-0.061	Estimated considering the changes in the leaching due to straw removal
Indirect N_2O-N[7]	Kg	0.032	0.0075*NO_2-N+0.01*(NH_3-N+NOx-N) (IPCC 2006).

Assumptions:

[1] [Composition of straw (85% DM); C=47.3%, N=0.6%, P=0.09%, K=1.5%] (Møller et al. 2005)

[2] Soil C sequestration= C content in straw*0.85*8.8% = 47.3%*1 t*0.85*8.8%.

[3] kg of N in the crop residues (1 t straw, 85% DM) =0.6%*1 t straw*0.85=5.1 kg

[4] kg of P in the crop residue (1 t straw, 85% DM)*(Ratio of Mol. wt) =0.09%*1 t straw*0.85*(142/62).

[5] Kg of K in 1 t of straw (85% DM)*(Ratio of Mol. wt) = 1.5%*1 (kg)*0.85*(45/78).

[6] NO_3-N (from additional fertiliser)= Additional fertiliser-N application –N output in straw removed-N emissions from additional fertiliser -N application-(-N_2O-N from crop residues-N build up in soil) (Nguyen et al. 2013)

[7] Indirect N_2O-N = 0.0075*4.3+0.01*(0.0306+0.0107)

Figure 2 illustrates the environmental impacts in association with the relevant process evolved due to removal of 1 t (85%DM) of the straw. As discussed earlier, soil C build-up is avoided due to this process, which has consequences to the soil nutrient buildup. This thus results to increase the GWP, particularly equivalent to the amount of avoided soil C sequestration potential from the residues and from the production of the compensating amount of fertilisers. For e.g. in the case of GWP, 87% of the total GWP per reference flow of the feedstock is because of limiting the soil C sequestration potential, and the rest is because of manufacturing process of chemical fertilisers. Likewise, 100% of increased fossil fuel consumption is associated with the manufacturing process of compensating fertilisers (Figure 2). These consequences are irrespective of how the application of the removed straw is taking place. In section 3.2, we have assessed the environmental impacts with respect to utilisation of the removed straw in the chain of district heat production.

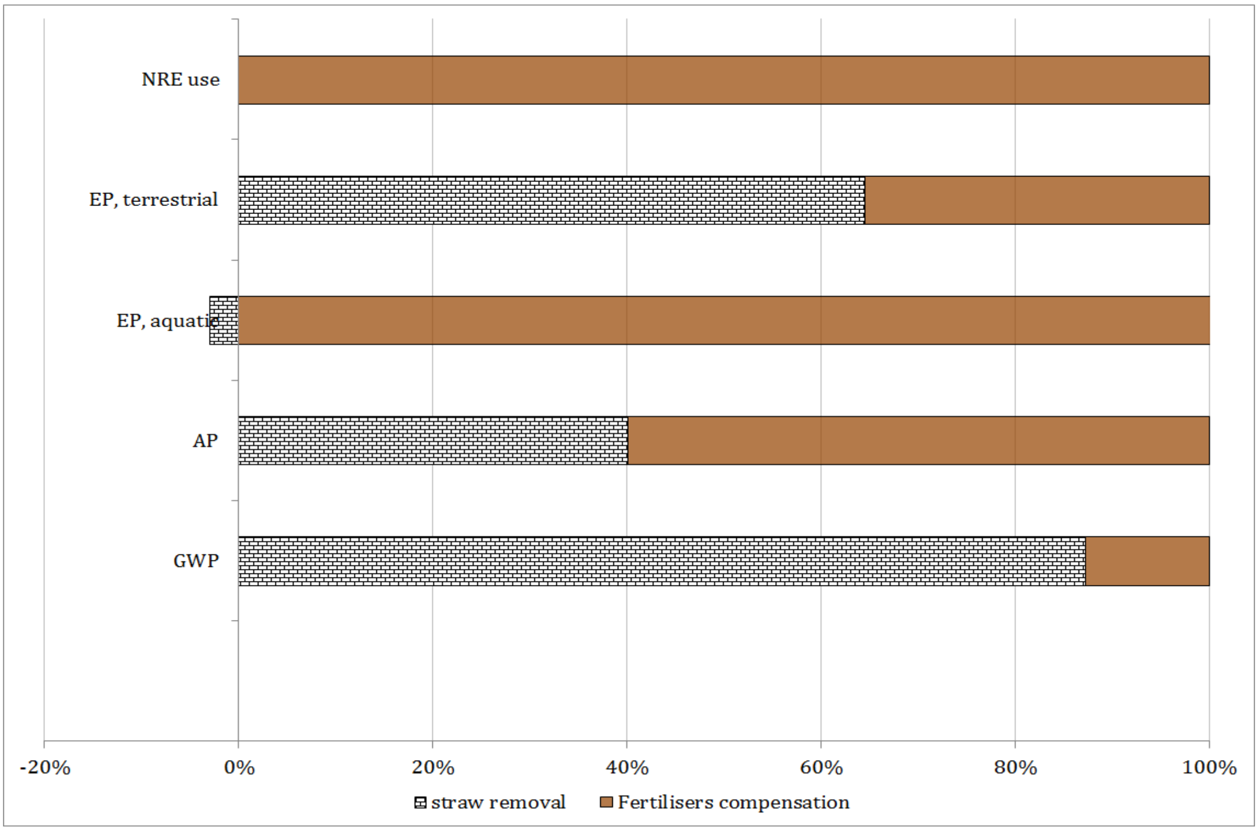


Figure 2: Environmental impacts in relation to removal of 1 t (85%DM) straw

3.2. Comparison of environmental impacts of district heat production in a CHP and boiler

In the case of CHP, we have assumed that the substitutable marginal electricity is a coal fired plants. We have presented the environmental impacts in gross and net values, the former represents the positive (+) impacts associated with the energy conversion processes, and the latter represents, “gross impact minus impacts that are displaced”. Here displaceable impacts are the environmental impacts associated with co-products: electricity and nutrients values of slag. In the case of CHP both co-products are accounted, otherwise only the latter is considered in the case of boiler. In the case of CHP the equivalent amount of electricity which is assumed to be displaced while producing 1 MJ district heat is estimated at 0.416 MJ, with 25% electric efficiency of the plant, and with the estimated fuel input equivalent to 1.66 MJ.

It should be noted that in Figures 3.a-3.e the environmental impacts connected with the downstream sides represent the gross values (i.e. environmental performances of co-products not included), which is presented separately in the same figures.

3.2.1. GWP

The gross GWP per MJ of district heat production in a boiler is 23.22 g CO_2-eq, of which 76% is because of GHG emissions associated with the upstream processes and the rest of it is in relation to the downstream processes. The higher GWP in the up-stream side of the energy conversion is associated with the emission of C to the atmosphere, which would have been sequestered if the straw is plough back to the soil. This corresponds to 15 g CO_2-eq /MJ heat, representing 65% of the gross GWP alone. Likewise, other processes of the upstream side, such as Collection and pre-processing, baling and handling, and transportation is responsible for 10%, 2% and 7% respectively of the gross GWP. The downstream side, particularly due to electricity input required during the initial combustion process, covers 21.5% (5 g CO_2eq/MJ heat) of the gross GWP. We have assumed that 110 kWh electricity is required per t of straw (Nielsen 2004). This amount of electricity is assumed to be feed-in from the electricity mix of Denmark, the LCI of which is based on Ecoinvent Centre (2010). The co-product in the case of the boiler is only the nutrient values of the slag, which is found having emission reduction of -0.027 g CO_2-eq/MJ heat, which is very insignificant to the gross value (23.22 g CO_2-eq/MJ heat). The detail breakdown of the GWP at the different stages of energy conversion processes and production of heat in a boiler are shown in Figure 3.a and Figure 4.a.

In the same manner while producing 1 MJ of district heat in a CHP, the net GWP is -86.54 g CO_2-eq. The gross GWP in the energy conversion process of the straw and finally producing heat in a CHP is 25.86 g CO_2-eq /MJ heat. Of this gross GWP, 96% is contributed by upstream process and rest by the downstream processes. Similarly, the straw removal process, alone contributes 83% of the gross impact (Figure 4.b). Collection and pre-processing, and transportation of the straw are found covering 13% and 9.5% respectively of the gross impact. Electricity as a co-product is found displacing 112.36 g CO2-eq/MJ heat, if coal is considered as the substitutable marginal electricity. Likewise, the nutrient values in the slag displace the 0.04 g CO2-eq/MJ heat.

3.2.2. Acidification Potential

The AP in relation to the production 1 MJ of heat in a boiler unit is 0.0079m^2 UES. There is no any significant difference in the AP between the cogeneration unit and a boiler unit. The reason behind this is that the acidification is mostly influenced by the direct emissions (combustion), and the co-products such as electricity possess insignificant role to lower this impact (Figure 4.a), and the net fuel inputs are estimated closely in both types of combustion system (Table 1). Electricity as a co-product could reduce the AP by -0.0029 m^2UES/MJ heat if straw is fired in a CHP, and nutrient values in the slag have insignificant reduction (Figure 3.b).

3.2.3. Eutrophications

The net EP (aquatic) per 1 MJ of heat production in a boiler is 0.09 g NO_3-eq, where the gross impact is estimated at 0.1 g NO_3-eq. The gross impact is basically higher in the upstream side of the energy conversion. The EP (aquatic) is entirely related with consequences of the straw removal process, as discussed in section 3.1. For e.g. with respect to gross EP (aquatic), the straw removal covers 87.4 % (i.e. 0.087 g NO_3-eq/MJ heat) (Figure 4.a).Impact of displacing the fertiliser by the co-produced slag is insignificant compared to electricity (Figure 3.c). Similarly, in the case of CHP, the net aquatic EP is 0.13 g NO_3-eq/MJ heat, which is 1.4 fold lower compared to the boiler. The co-produced electricity and the nutrient values in the slag displace the impact at the rate of -0.01 g NO_3-eq/MJ heat and -0.006 g NO_3-eq/MJ heat respectively (Figure 3.c).

The terrestrial EP in the case of boiler is 0.0067 m^2 UES/MJ heat, where the co-products of the system do not have any significant role to reduce the impact (Figure 3.d). Terrestrial EP is primarily because of the downstream process, contributing 80% of the gross impact, where the combustion alone leads to cover 75.6% of the gross impact (Figure 4.a). The net terrestrial EP in the case of producing 1 MJ of heat in a CHP is 0.006 m^2 UES, where about 0.003 m^2 UES is reduced in the gross impact (0.009 m^2UES) due to co-products (Figure 3.d). 21% of the gross terrestrial EP is due to upstream process, where the straw removal has the highest contribution. Likewise, the downstream process covers the rest of the impact, where combustion alone contributes 78% of the gross impact (Figure 4.b).

3.2.4. NRE Use

The gross NRE use in the straw fired boiler is estimated at 0.134 MJ-primary/MJ heat (Figure 3.e). Of the gross NRE use, the upstream process covers 43% and rest by the downstream process. Electricity input required for the combustion process (at the downstream side) alone contributes 54% of the gross impact. The nutrient values of the slag produced displaces insignificant amount of the NRE use, which is estimated at 0.0004 MJ-primary/MJ heat.

If the same amount of heat is produced in a CHP, the gross NRE use is estimated at 0.088 MJ-primary/MJ heat. Whilst, the net NRE use in the entire life cycle process of the energy conversion is -1.23 MJ primary/MJ heat (Figure 3.e). The co-produced electricity displaces substantial amount of fossil fuel consumption, which is estimated at -1.32 MJ-primary/MJ heat, which represents the displacement of coal. Hence, this displacement would not have been possible if cogeneration unit is not considered.

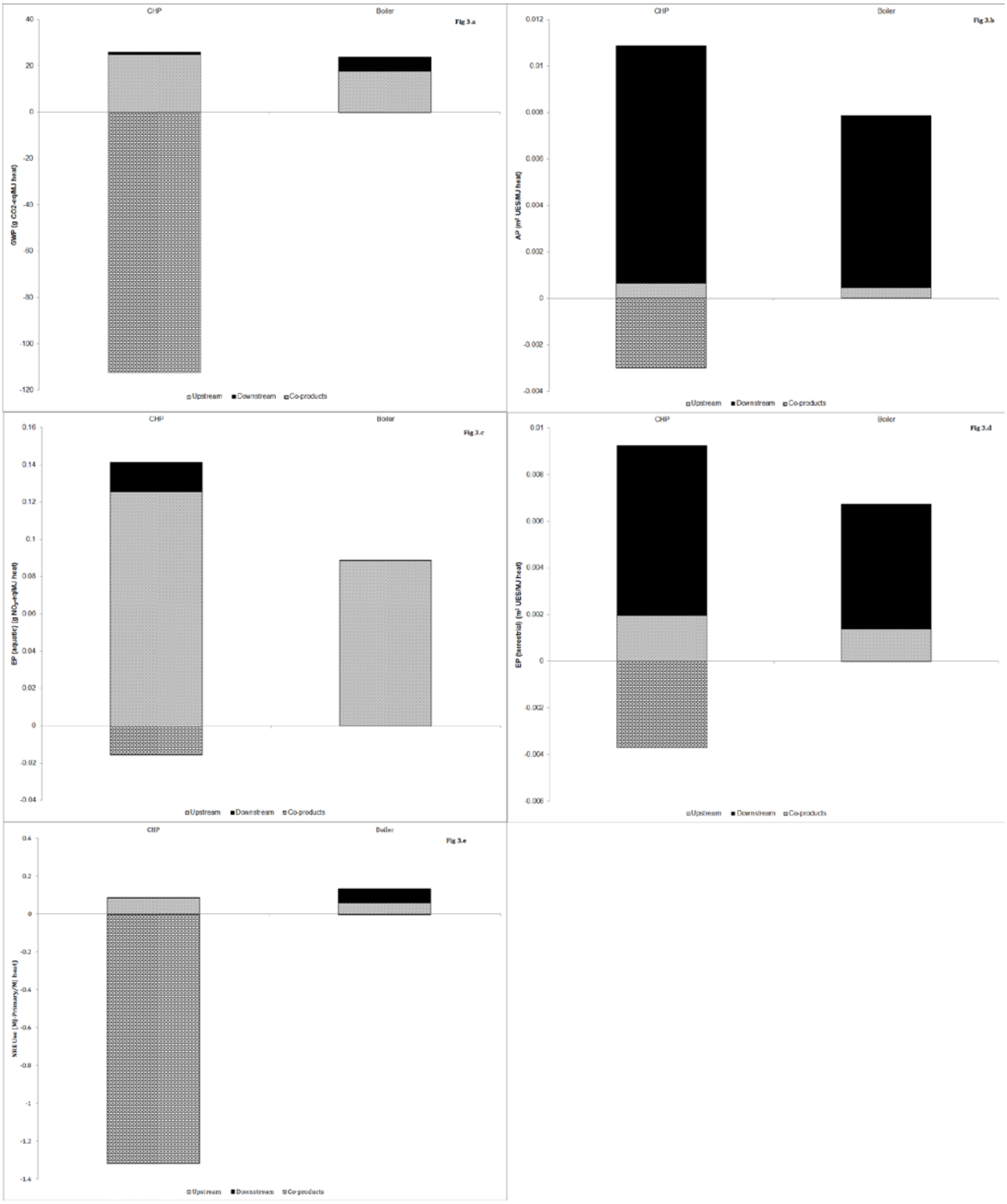
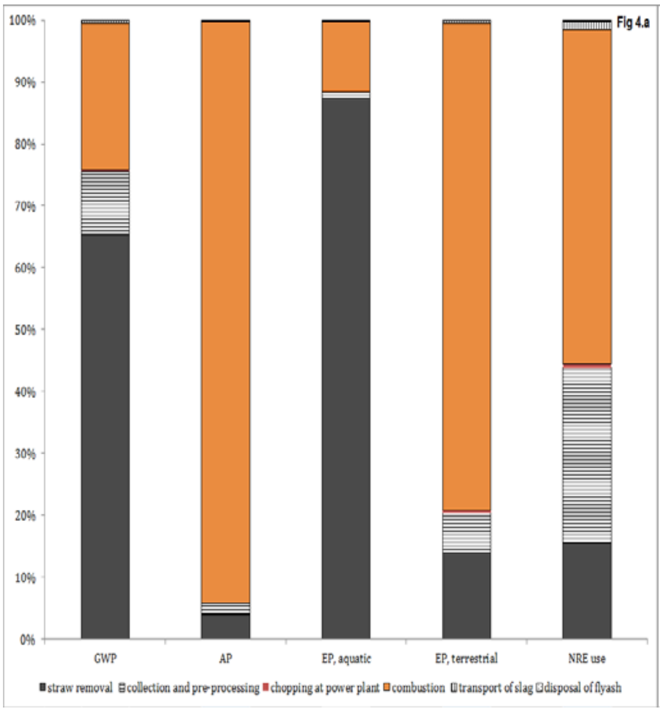


Figure 3: Environmental impacts of the straw fired district heat production in a CHP and a boiler.



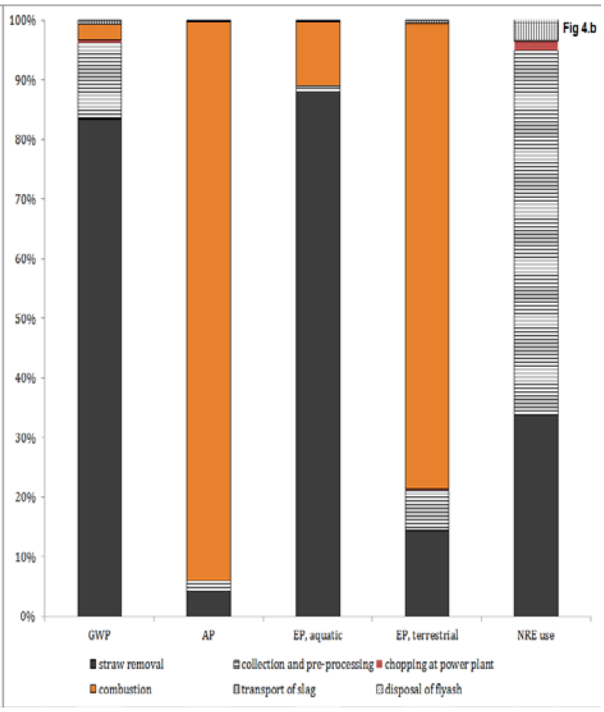


Figure 4.a: Environmental hotspots of straw fired district heat production (Boiler)

Figure 4.b: Environmental hotspots of straw fired district heat production (CHP)

3.3. Producing 1 MJ of district heat in a straw and natural gas fired cogeneration unit under different substitutable marginal electricity productions.

In section 3.2, we discussed about the potential benefits of straw fired cogeneration unit with respect to the boiler. We made an assumption that the co-produced electricity displaces the environmental impacts of coal-based marginal electricity production. But at the meantime, there are some debates on the marginal electricity productions (Weidema et al. 1999; Ekvall and Weidema 2004; Mathiesen et al. 2009). Among them, long term/short term effects of electricity substitution are regarded as a measure for defining the marginal electricity (Weidema et al. 1999; Ekvall and Weidema 2004), whereas Ekvall and Weidema (2004) discussed from the perspectives of market proportion and competitive alternatives available in the market. Likewise, Mathiesen et al. (2009) argued from cost of production of the alternatives and future energy management perspectives. Weidema et al. (1999) argued from the standpoint of an environmental regulations and also highlighted that due to lower capital cost, natural gas fired power plants were regarded as marginal technology in the Nordic electricity market. The official Danish energy policies of 2003 has spelled about the natural gas as the marginal production, where fuel prices were relatively lower (Mathiesen et al. 2009). Likewise, coal can be constrained from the environmental regulations, such as carbon quotas, but differs in individual countries (Weidema et al. 1999). As per the Danish 2005 energy policy, which had CO_2-quota prices included on top of the expected three different fuel prices, wind power was identified as the marginal technology, but in the same study wind power is disregarded as the marginal technology from its responses to changes in demand and its spatial production i.e. differing from one region to another.

Considering these uncertainties, we made a comparison of environmental performances in relation to the straw and NG as fuel alternatives in the district heat production in a CHP. The substitutable marginal electricity indicated in Figures 5-6 are represented as 'me1', 'me2', 'me3', which nominate for the technologies natural gas, coal and Wind power respectively. The life cycle impact in relation to 1 kWh of electricity production with the coal and Wind power are based on Ecoinvent Centre (2010) and for the natural gas is based on the LCA Food DK, all these database are imported from the tool SimaPRO 7.3.3.

When we compare our results between straw and natural gas as fuel alternatives, we have found that despite the straw fired heat production leads to lower GWP and NRE Use, but has higher AP and EP compared to the latter (Figure 5-6).

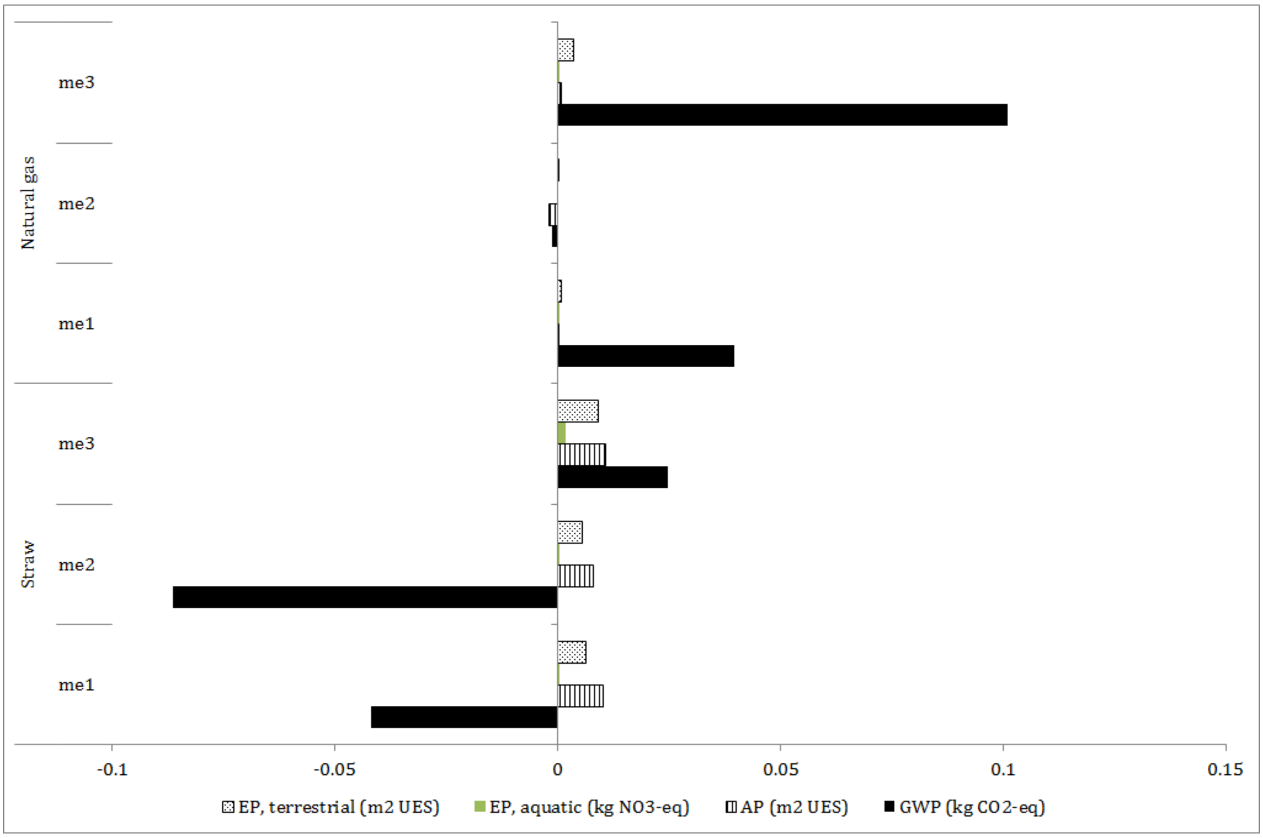


Figure 5: Environmental impacts of straw and natural gas fired district heat production (in a CHP with three situations of marginal electricity).

Furthermore, when the influences of marginal electricity are taken into considerations, we have found that the displacement of the coal based marginal electricity offers better environmental performances compared to the displacement of the other two marginal electricity production. If the electricity produced from the straw fired CHP displaces the coal fired power production, the district heat production could lead to GWP of -86.54 g CO_2-eq/MJ heat, whilst for the same marginal electricity natural gas fired in the CHP leads to -1.41 g CO2-eq/MJ heat. In the same manner, if coal is the substitutable marginal electricity then NRE use in the case of straw and natural gas fired district heat production are -1.23 MJ-primary/MJ heat and 2.1 MJ-primary/MJ heat respectively (Figure 6).

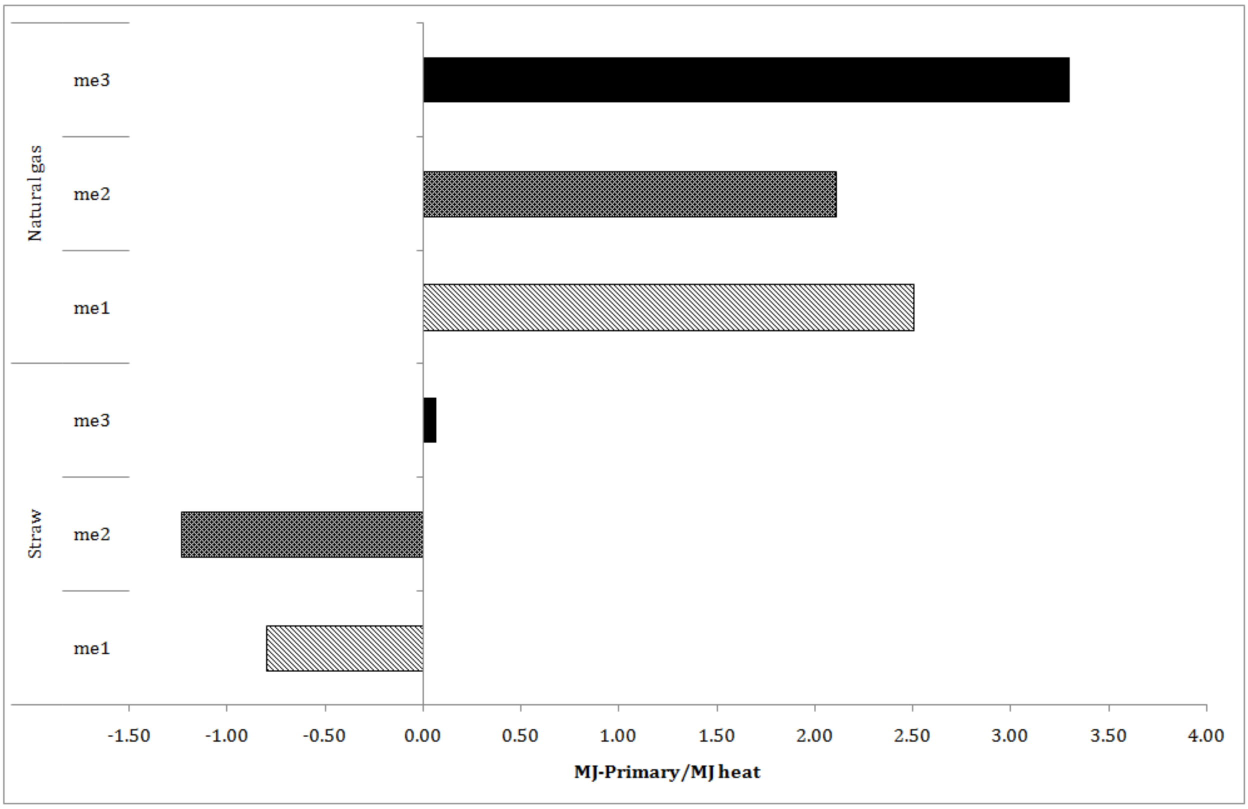


Figure 6: NRE Use (MJ-primary/MJ heat) in the straw and natural gas fired district heat production (with three situations of marginal electricity).

4. Environmental issues and possible solutions

In the earlier sections, it is discussed that despite the straw as a fuel input for district heat production is attractive from the standpoint of GWP and NRE use, but has higher EP and AP. Furthermore, in the environmental hotspots assessments (Figure 4), the aquatic EP is primarily associated with the consequences of straw removal process. Some studies including McLenaghen et al. (1996) and Kirchmann et al. (2002) reported that improvement of agricultural management practices could be a solution for controlling the nitrate leaching. Similarly, Martinez and Guiraud (1990) highlighted about the integration of winter "catch crops" in the agricultural system, which is possibly carried out after the removal of straw so that field are not remained fallow, as leaching is more when the agricultural field is fallow (Eriksen and Thorup-Kristensen 2002). The advantage of catch crops, such as rye grass normally decrease leaching loss by absorbing much of the mineralised N back into the organic pool (Whitmore and Schröder 2007). These potential solutions to lower the leaching losses not only help to reduce the environmental impact but also ensure the production of additional biomass either for energy purposes or for animal feed. Furthermore, application of animal manure also supports in reducing the nitrate leaching compared to the situation that would occur with inorganic fertilisers (Bouwman et al. 2002).

LCA of such additional interventions could be carried out to investigate about to what level EP can be controlled.

Likewise, the terrestrial ecosystem, mainly affecting the higher plants is caused due to Nitrogen (N) as the major limiting nutrient, when concentration of NOx and NH_3 increases in the ecosystem (Brentrup et al. 2004) making the environment eutrophic. From the hotspots analysis we have found that terrestrial EP is mainly due to emissions from the combustion process, hence improvement in the combustion system to reduce NOx in particular could reduce this effect.

From Figure 4.a and 4.b, it is found that AP is mostly associated with the downstream process of energy conversion, and in particular from the combustion of the straw. The AP is higher in a straw fired heating plants due to higher emissions of chlorine, sulphur and NOx compared to wood fuel (Pehnt 2006). Furthermore, it is more triggered from the emissions related to inorganic fertiliser applications and other material inputs during the processing of the biomass. One of the possible means of controlling the acidification at a technological level is adopting the desulphurisation technology (EC 2006) in the combustion process. Generally, desulphurisation technologies such as, the wet scrubber is found able to reduce the SO_2 emissions at the rate of 92%–98%, and the spray dry scrubber technology reduces at the rate of 85-92% (Kaminski 2003; EC 2006).

Similarly, NOx emissions may be controlled by adopting modifications in the combustion process such as, separating the combustion process in stages, which partially delays the combustion process and results in a cooler flame that suppresses thermal NO*x* formation (EC 2006). There are other possible alternatives to lower the NOx emissions such as combustion in low excess air, and recirculate part of the flue gases into the combustion air, which prevents NOx formation (Graus and Worrell 2007). Flue gas condensation technologies is also popular for straw firing technologies in Denmark, and is reported to increase the thermal efficiency with 5-10% and reduces SO_2 emission to a minimum level (energinet.dk 2012). Likewise, NOx emissions may be reduced at the rate of 60-70% by adopting a non-catalytic reduction (SNCR) technology.

5. Conclusions

The assessment of environmental impacts in relation to 1 MJ of district heat production discussed in this study can be concluded in following points;

- For every 1 MJ of district heat production, the straw fired CHP plant could lead to a GWP of -86.54 g CO_2-eq, AP 0.008 m^2UES, aquatic and terrestrial EP at 0.13 g NO_3-eq and 0.006 m^2UES respectively, and NRE use -1.23 MJ-primary. For the same amount of heat output, straw fired in a boiler leads to GWP of 23.73 g CO_2-eq, AP 0.008 m^2 UES, aquatic and terrestrial EP 0.09 g NO_3-eq and 0.0067 m^2 UES respectively, and NRE use of 0.13 MJ primary.
- Straw fired district heat production is better than NG in a cogeneration system, in particular from the perspectives of lower GWP and NRE Use. In the latter case, the GWP and NRE use are -1.41 g

CO2-eq/MJ heat and 2.11 MJ primary/MJ heat respectively, with coal as the substitutable marginal electricity. But for other impact categories, NG fired district heat production shows better environmental performances. For e.g. compared to straw it leads to AP of -0.002 m^2UES/MJ heat, and the aquatic and terrestrial EP of -0.001 g NO_3-eq/MJ heat and 0.0002 m^2UES/MJ heat respectively.

- In the case of CHP, the substitutable marginal electricity has an influential role in lowering the environmental impacts of straw fired district heat production.

Finally, straw fired CHP plant to produce district heat could play an important role in conjunction with other fluctuating renewable energy technologies, such as Wind power in the Danish future renewable energy goal, not only maintaining the local energy demand but also serving as storable forms of energy carriers.

Apart from the above mentioned advantages of straw as a fuel input, there are other potential applications of straw such as animal feed and building materials, but we have not compare the environmental performances of such applications in this study. This opens avenues for the assessment of environmental impacts of removed straw and its other applications besides heat/power production. Similarly, possible integration of catch crop cultivation beyond the stage of removing the straw and its further utilisation in heat/power production could be considered for further research, so that life cycle impacts of such system expansion could give idea about the environmental feasibility of such considerations. Likewise, economic and life cycle impact of using the modern technologies to reduce the SO_2 and NOx emissions could be further carried out.

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