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ORIGINAL PAPER

Development of net energy ratio and emission factor for quad-generation pathways

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Abstract The conversion of biomass to four different outputs via gasification is a renewable technology that could reduce the use of fossil fuels and greenhouse gas (GHG) emissions. This study investigates the energy aspects for a new concept of biomass based quad-generation plant producing power, heat, methanol and methane. Circulating fluidized bed gasifier and the gas technology institute (GTI) gasifier technologies are used for this quad-generation process. Two different biomass feedstocks are considered in this study. The net energy ratio for six different pathways having the range of between 1.3 and 7.2. The lowest limit corresponds to the wood chips-based power, heat, methanol and methane production pathway using GTI technology. Since more efficient alternatives exist for the generation of heat and electricity from biomass, it is argued that syngas is best used for methanol production. The aim of this study was to evaluate the energy performance, reduce GHG and acid rain precursor emission, and use of biomass for different outputs based on demand. Finally, a sensitivity analysis and a comparative study ar conducted for expected technological improvements and factors that could increase the energy performance.

Keywords Net energy ratio · Quad-generation · Feedstocks · Syngas

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1 Introduction

Biomass is a limited resource that needs to be used efficiently with low environmental impact, from extraction, conversion and distribution to end use. Biomass, including agricultural residue (i.e. straw, corn stover), forest residue (branches and tops of the trees), whole tree, and energy crops can be used to produce a range of fuels and chemicals. In Denmark, biomass currently accounts for approximately 70 % of renewable-energy consumption, mostly in the form of straw, wood and renewable wastes. Consumption of biomass for energy production in Denmark more than quadrupled between 1980 and 2005 [1,2]. The consumption of biomass (straw, woodchips) for electricity and district heating has increased significantly.

Biomass conversion can be divided into two main pathways: thermochemical conversion and biochemical conversion [3]. Biomass can also be refined through essentially mechanical treatment such as extraction (e.g. oil from seeds) or pelletizing. The thermochemical pathway can be further subdivided into combustion, gasification and pyrolysis [4]. Biomass combustion is widely applied to generate heat and electricity on a wide range of scales. Gasification converts the biomass into a gas that can subsequently be used to generate heat and electricity or be converted into fuels or other chemicals [4–6]. Pyrolysis converts the biomass into a mixture of char, liquid and gas, and is usually considered as a pre-treatment option for long-distance transport. The biochemical pathway can be divided into two main paths: digestion and fermentation into methane and ethanol, respectively [3]. Other biochemical pathways are also possible, such as anaerobic production of acetone and butanol together with ethanol [7], but less attention is devoted to them today. The conversion of biomass to polygeneration output via gasification and combustion technologies is a renewable technology that could substitute fossil fuels [8–12].

The energy related CO_2 emissions are responsible for the majority of Denmark's total emissions of greenhouse gases, approximately 78 % in 2009 [1]. Therefore, the energy baseline scenario has large impact on the expectations for future emission levels and possible deficits in relation to international obligations. Green house gas (GHG) emissions from agricultural sector are predominantly relevant to facilitate a more sustainable development, and to achieve the stabilized GHG emissions and global mean temperature targets of Kyoto Protocol, 1997 and Copenhagen Accord, 2009. In this context, Denmark is committed to a 21 % reduction in GHG emissions from 1990 to 2012 [13], and in addition Denmark has agreed a national ambition of a society independent of fossil fuels by 2050. The annual GHG emissions from the primary agricultural sector in Denmark in the form of nitrous oxide (N_2O) and methane (CH_4) are currently about 10 Tg (1 Tg $= 10^9$ kg) carbon dioxide equivalents (CO_2eq) compared to total emissions of 66 Tg CO_2eq for Denmark in 2010 [14]. Furthermore, around 5 Tg CO_2eq should be added CO_2 emissions from direct and indirect fossil energy use [15], and a net mining of the soil carbon pools (DC) amounting to less than 1 Tg CO_2eq [16]. Other GHG contributions from agriculture are negligible. Methane and nitrous oxide emission from agriculture amounted in approx. 15 %, emissions from waste (landfill) and discharged water amounted to approx. 2 % and energy-related emissions amounted for approximately 3 % [17].

There are few studies which have done comparative analyses of different biomass feedstock conversion pathways for biofuels and hydrogen [12, 18–20] but none of these studies investigate different biomass conversion technologies for producing power, heat, methanol, and methane from straw and wood chips. The objective of this paper is to quantify environmental impact in terms of emissions and NERs for different quad-generation production pathways. Two different technologies for producing four products are analyzed: circulating fluidized bed (CFB) and gas technology institute (GTI). These technologies are described in subsequent sections.

1.1 Quad-generation pathways

Biomass fueled combine heat and power (CHP) plants have now for many years been a common part of the Danish electricity and district heating supply. The development of energy-efficient production technologies has made cogeneration and tri-generation possible, and now, the development trend is moving towards quad-generation and poly-generation. The net energy ratio analysis has done for quad-generation. Table 1 gives the description of quad-generation plant size description and technologies. Sixteen different pathways have been considered in this study. Figure 1 shows the different conversion pathways.

Table 1 Plant size for quad generation pathways

Technology	Feedstock	Optimum size, dry tons per day (dtpd)	Comments/sources
CFB	Straw	1,000	These key features have been derived from an earlier study by Ruhul and Kumar [12]. The size of the each gasifier unit is assumed to be 1,000 dtpd
	Wood chips	1,000	
GTI	Straw	1,000	The size of the plant is derived from Sarkar and Kumar [10]. The capacity of each gasifier unit is assumed to be 1,000 dtpd
	Wood chips	1,000	

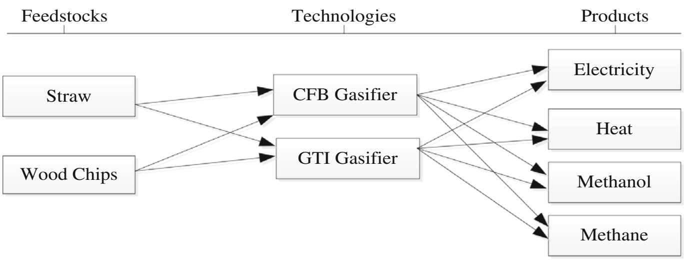

Fig. 1 Biomass conversion pathways for quad-generation

2 Methodology

The quad-generation plant is produced syngas via gasification which is then used for generating power, heat, liquid fuel (methanol) and gaseous fuel (methane). Different products production pathways are analyzed as a combination of several unit operations. Materials, equipments, and fuel-embodied energy and emissions factors are determined for each of the unit operations involved in a conversion pathway over its life cycle.

Since power, heating, liquid and gaseous fuels are measured in different units (e.g. MJ, kW and m^3); the functional unit is defined as the use of 1 MJ of syngas in either one of these applications. It means the quantity of a service (power, heat, methanol and methane) that is delivered by '1 MJ of syngas'. These values are the basis for the calculation of the net environmental benefit, which is used to compare the environmental advantages resulting from the substitution of different reference systems by syngas systems. It is calculated therefore as the difference between the impacts generated by syngas and reference systems. This study evaluates the NERs for all quad-generation pathways, a crucial ratio for the assessment of renewable systems. The NERs for the pathways are calculated using Eq. (1) [12].

$$NER = \frac{\sum E_{out}}{\sum E_{in}} \tag{1}$$

where, $\sum E_{in}$ = life cycle non-renewable primary energy input corresponding to the functional unit (FU) of a pathway, and $\sum E_{out}$ = energy available from the FU equivalent MJ syngas produced from the pathway. It should be noted that this study is based on the lower heating value (LHV) for fuels. Two environmental stressors i.e. net GHG emissions and acid rain precursors (ARP) are considered for emission analysis. These two environmental stressors for a particular conversion pathway are calculated using Eq. (2) [12].

$$\text{Net emission} = \sum \varepsilon_{out} \tag{2}$$

where, $\sum \varepsilon_{out}$ = life cycle emissions corresponding to the FU of a pathway within the defined system boundary (Fig. 2). GHG stressors are reflected to be mainly carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), and nitrous oxide (N_2O). GHGs contribute to global warming. The global warming potential (CO_2eq) for these gases are assumed to be 1, 3, 21, and 310 respectively.

Energy consumption and emission are estimated for all the unit processes. All the key activities from farming to quad-productions have been considered apart from the irrigation and electricity distribution to the grid and final consumer. A consolidated system boundary for the current LCA study is showed in Fig. 2.

To compensate for variations in electricity demand during the day and the year, the power generated at the farm is assumed to be supplied to the Danish national grid and from there retrieved by the households.

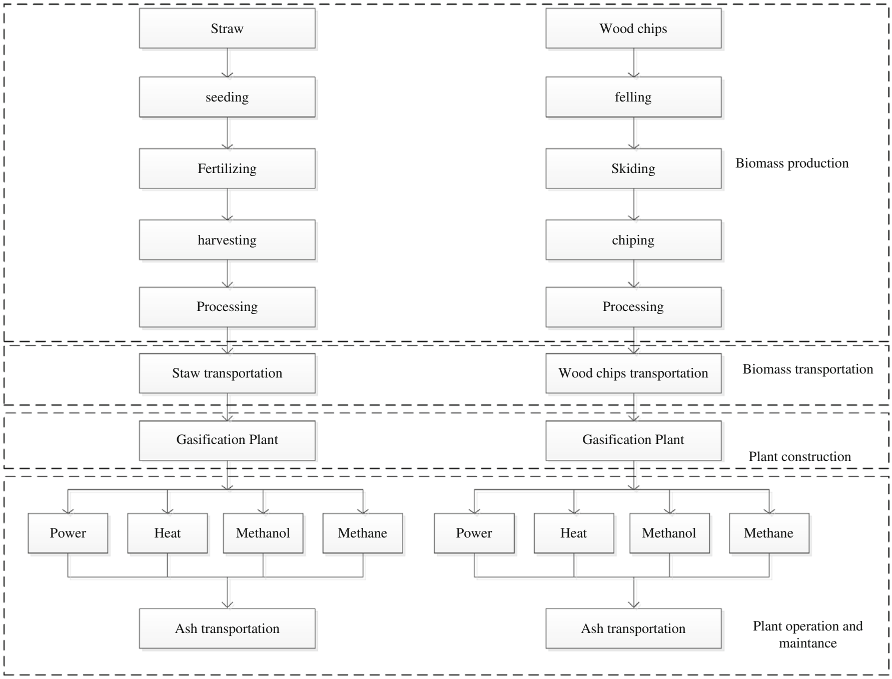

Fig. 2 System boundary for quad-generation pathways

3 Assumptions of unit processes

The unit processes that have been considered for CFB and GTI technologies are: biomass production/supply (mainly includes seeding, production and distribution of fertilizer, herbicide and pesticide production and distribution, harvesting, manufacturing and decommissioning of all the equipments used in every stage, raking, baling, bale moving and wrapping), biomass transportation (mainly includes loading and unloading, transportation by truck), plant construction, maintenance and decommissioning, plant operation, (mainly includes shredding, plant utilities, ash disposal and regular operation) and quad-productions (mainly includes power, heat, methanol and methane production, methane transportation).

3.1 Biomass production/supply

Denmark is in a very superior position regarding utilization of straw, partly because energy politics since the beginning of the eighties have put a strong effort in implementing biomass in the energy supply, and partly because straw is a very essential biomass resource in Denmark [21]. For the period from 2004 to 2008 the total straw production in Denmark was 5.5 million tons/year (82.5 PJ at 15 % water) where 1.4 million tons was used for combustion. This gives a surplus of 2.2 million tons straw/year or 40 % of the total production [1]. The straw-to-grain ratio is assumed to be 1.1:1 on the basis of its mass fraction [22]. Accordingly, a portion of the impact from common operations for straw and grain (from cultivation to harvesting) is allocated to straw. Wood chips are also only harvested in softwood stands, but by producing wood chips from hardwood, such as beech, the yield of wood chips can be greatly increased when using nurse trees. By planting hybrid larch also, the yield of wood chips could be tripled in proportion to a pure beech stand. It is justified to believe the machinery selection with agricultural practices to be more common.

3.2 Biomass transportation

As an operation in the collection process, straw is transported as bales from the field to the road side. Then these bales are transported to the power plant. In a complete life cycle analysis of freight transportation, life cycle phases of vehicles, infrastructure and fuels have to be included [23–25]. However, since the plant location is not exactly determined in the study, the infrastructure for transportation which includes the construction and maintenance of roads is assumed as already existing and no significant road construction required. It has been assumed that an average transport distance from the forest road to the plant of 20 km (own calculation), and that transport takes place with 25 tons lorry.

3.3 Plant construction, decommissioning and disposal

The construction material required for the different plants is estimated using data given in earlier studies [12,26]. Scale factors are assumed to be 0.76, 0.68, 0.78 and 0.70, respectively, for BCL, GTI plants and are based on detailed analyses reported in earlier studies [10,11]. Scale factor is defined by the following equation [27].

$$\frac{C_i}{C_o} = \left(\frac{S_i}{S_o}\right)^n \tag{3}$$

Where C_i, C_o = cost at size ‘i’ and at reference (o) units, respectively. S_i, S_o = size or rating of the corresponding units, and n is the scale factor. Note that, material-embodied energy and emissions are considered over their life cycle.

3.4 Plant operation and maintenance

The major environment benefit of biomass energy is that theoretically it’s a carbon neutral energy source once the full life cycle is considered. In simple, the CO_2 emitted during the conversion of biomass energy is considered to be the atmospheric CO_2 absorbed by the plants during the growth phase. However, this balance exists between the biomass growth and conversion emissions only.

3.4.1 Circulating fluidized bed (CFB) gasifier

The circulating fluidized bed (CFB) gasification technology is used [28] for this study. Several alternative gasification technologies exist (energy efficiencies, suitability for

SNG, and other process details are discussed in [29,30]). The CFB gasification process consists of separate gasification and combustion chambers. In the gasification chamber, hot steam and the bed material olivine are used as energy carriers to gasify wood under the absence of oxygen. The resulting producer gas consists of hydrogen, carbon monoxide, carbon dioxide, and methane as well as other hydrocarbons, tars, and ash. In the combustion chamber the energy required to maintain this endothermic process is transferred to steam and olivine through the combustion of wood and incompletely gasified wood fractions (coke and tars). During gasification, tars as well as other substances are formed from traces of nitrogen, sulphur, chlorine, and metals contained in the wood and transferred into the product gas, from which it needs to be cleaned. This is done in several steps including a baghouse filter to remove particles as well as a washing step with rape methyl ester (RME) as organic solvent to remove water and tars.

3.4.2 Gas Technology Institute (GTI) gasifier

In the case of GTI pathways, the electricity produced by the plant is enough to support the feedstock pretreatment processes and other plant operations [31]. Once again, credits from selling extra electricity to the grid are not considered. In addition, natural gas need not be purchased for these pathways. So, for GTI pathways ash disposal is the only plant operation that needs to be accounted for.

3.5 Quad productions

This unit process is relevant to both CFB and GTI pathways. It includes power, heat, methanol and methane production. It is assumed that the quad-generation plant has access to the national natural gas grid. In this context, a process that converts biomass into methane does not require any transportation. It is assumed that, methanol is transported for 200 km. Methanol has low density that only 300 kg methanol can be carried using a conventional 36 tons payload truck [32].

4 Inventory assessment for life cycle calculation

4.1 Biomass properties and plant characteristics

The yield and physical properties of biomass are very critical to performing NER analysis for biomass-based systems. These have a significant impact on various upstream and downstream operations of biomass conversion such as transportation, feedstock pretreatment, plant mass and energy balance, plant maintenance, etc. The biomass inventory data and general plant assumptions are given in Table 2.

4.2 Fuel and fertilizer requirement

Almost all the unit processes used fossil fuel as the primary energy input. Methanol is required to methane and methanol production. Almost 68 % of all the electricity

Table 2 Biomass properties and general assumptions

Properties	Straw	Wood chips	Comments/references
Moisture content (%)	7.5–12	45	These are the moisture contents of as received feedstocks. It is assumed that moisture contents would not change transportation of feedstocks after preliminary processing [33,34]
Bulk density (kg/m^3)	130	300	
Lower heating value (MJ/dry kg)	15	10.5	[34,35]
Ash content (%)	4		[36]
Plant operating factor			These are conventional operating factors being used for biomass based plants[37]
Year 1	0.7	0.7	
Year 1	0.8	0.8	
Year 1	0.85	0.85	

Table 3 Energy input/output ratio and emission factors for electricity, different fuels and chemicals [12, 26,38–41]

Items	Diesel	Natural gas	Methanol	Electricity (unit/MWh)	Fertilizer (unit/kg)			Pesticide (unit/kg)
					N	P	K	
LHV (MJ/kg)	46.03	49.1	22.7	–	–	–	–	–
Density (kg/m^3)	832	0.78	792	–	–	–	–	–
kg CO_2eq/GJ	94.2	56.6	16	820	3.27	1.34	0.64	24.5
kg SO_2eq/GJ	0.37	0.13	2.00E−03	0.57	0.38	0.4	0.4	2.96
kg (NO_x + VOC)/GJ	0.59	0.22	1.00E−03	0.585	0.4	0.41	0.41	3.01
GJ/GJ	1.22	1.11	0.04	2.86	0.05	0.01	0.004	0.12

LHV lower heating value, *VOC* volatile organic compounds

generated in Denmark comes from fossil fuel-fired power plants [1,2]. Therefore, there are high emissions related to grid electricity. These emissions are estimated on life cycle basis. The efficiency with which natural gas is converted to electricity is assumed to be 45 %. Table 3 also shows the life cycle energy and emissions factors for different fertilizers and pesticides. The transportation inventory data include the production, use and disposal of trucks.

4.3 Inventory data for plant construction, decommissioning, and disposal

There are not many studies with primary energy and emissions related to decommissioning of a power plant. The steel, concrete and aluminum required to construct a GTI plant (for processing straw and woodchips), the material required is 5,084, 15,720, and 42 tons, respectively. To construct a CFB plant construction (for all the feedstocks), the necessary amount of steel, concrete and aluminum are needed almost 5,350, 16,535, and 44 tons, respectively [1,6,40]. However there are details of some limited research on this issue. According to these studies, primary energy input and relevant CO_2eq emissions for decommissioning are in-between 3 and 5 % of energy and emissions associated with the plant construction. Therefore, the decommissioning impact is assumed to amount to 3 % of the construction impact [42] for all plants.

4.4 Inventory data for plant operation and maintenance

The natural gas required to produce individual output from quad-generation using CFB gasifier has been found to be 0.12 m^3/m^3 syngas for both of the feedstock [28, 29]. Neither natural gas nor electricity purchases are required for GTI-gasifier-based quad-generation [30]. Methanol (10 wt%) is needed both for methanol and methane production. Inventory data for methanol have been given above Table 3. Ash is disposed 50 km away from the plant and is spread (1 tons ash/ha) to replace nutrients [12]. The ash content in methanol and methane is less than 0.1 %, hence, the impact from ash disposal is ignored in this study. The cleaned producer gas is used in a gas-powered heat, power, methanol and methane unit. Many studies have assumed a percentage of plant construction energy as the maintenance energy of the power plant, mostly between 2.5 and 5 % [42]. In this study, energy and emissions of plant maintenance is assumed to be 3 % of the plant construction energy and emissions in both cases.

4.5 Recycling and waste disposal

Steel, iron and aluminum used in all machinery, plant equipment and construction are considered to be recycled. The amount of steel used in farm machinery is considered as 98 % wherever it's not possible to find the exact value [43]. The energy and emissions needed to recycle these materials are considered in the analysis.

4.6 Inventory data for methanol transportation

Methanol has high density of 792 kg/m^3. This makes truck as a favorable mode of transportation along with the pipeline. It is assumed that methanol blend will be transported either using B-train truck of 60 m^3 capacity. Inventory data for methanol transportation are presented in Table 4.

5 Result and discussions

5.1 Life cycle energy impact

The total energy impact and NER corresponding to the functional unit for different GTI and CFB pathways are shown in Table 5. Note that, in order to determine NER, the LHV

Table 4 Methanol transport inventory data [12]

Mode	Category	Values	Comments/sources
Truck	Energy impact	0.85 $MJ/m^3/km$	Impacts include truck manufacturing, infrastructure construction, and truck operation. The authors evaluated other impacts based on the material inventory data from [44]
	Emission impact	56 gm $CO_2eq/m^3/km$	
		0.23 gm $SO_2eq/m^3/km$	
		0.36 gm $(NO_x + VOC)/m^3/km$	

Table 5 Life cycle energy performance of quad-generation pathways

Feedstocks	Technologies	Pathways	MJ/MJ syngas	kg CO_2eq/MJ syngas
Straw	CFB	PW 1	5.8661	1.1513
		PW2	7.2153	1.9733
		PW3	7.1243	1.9733
		PW4	6.8450	1.9733
	GTI	PW1	3.1562	0.2158
		PW2	3.2959	0.2158
		PW3	3.3257	0.2158
		PW4	3.0525	0.2158
Wood chips	CFB	PW1	4.3710	1.8797
		PW2	4.2212	1.8797
		PW3	4.4141	1.8797
		PW4	4.2036	1.8797
	GTI	PW1	1.2694	0.1847
		PW2	1.7669	0.1847
		PW3	1.9544	0.1847
		PW4	1.3703	0.1847

of methanol and methane has been assumed to be 19.6 and 38 MJ/NM^3 respectively [45]. Figure 3 shows the energy break down in all unit processes during the life cycle of quad-production for both straw and wood chips. In case of CFB pathways, the total energy impact for the both biomass feedstocks are comparatively higher than GTI pathways as plant operation and maintenance contributes significantly to the overall energy impact. Life cycle energy consumption corresponding to one functional unit is higher for fast pyrolysis pathway. The main reason is the feedstock pre-treatment and energy input for CFB. So, energy from framing and harvesting is almost double. In addition to that, more transportation distance is needed to be covered.

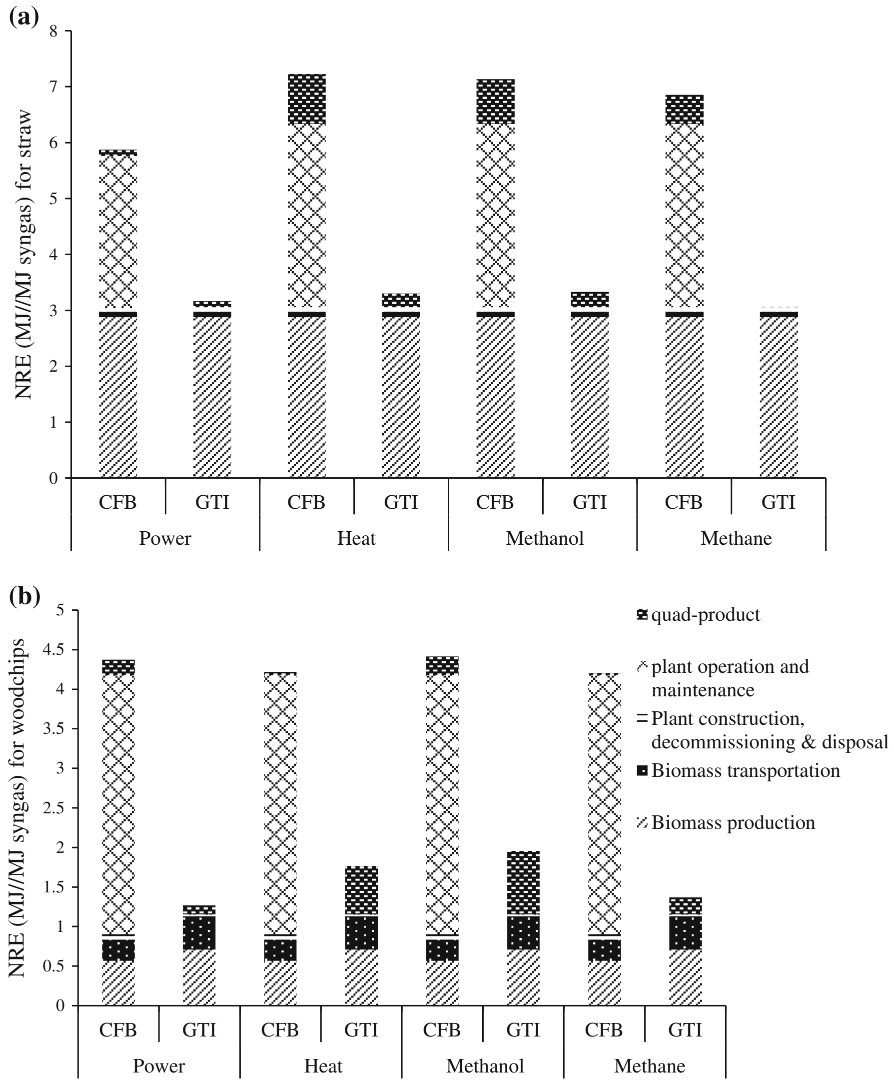

Fig. 3 NER graphs for both **a** straw and **b** wood chips

5.2 Life cycle emission impact

Life cycle GHG emissions from different pathways are depicted in Fig. 4. No greenhouse gas (GHG) emissions are generated during biomass growth. Wood transport by truck over short distances is rather efficiency and thus the use of diesel and generated air emissions only cause small impacts. Life cycle emission consumption corresponding to one functional unit is higher CFB straw pathways. The main reasons behind it are: net straw requirement for the same amount of power production is almost twice as syngas yield has been assumed as 50 wt% from triticale straw. It also has a similar

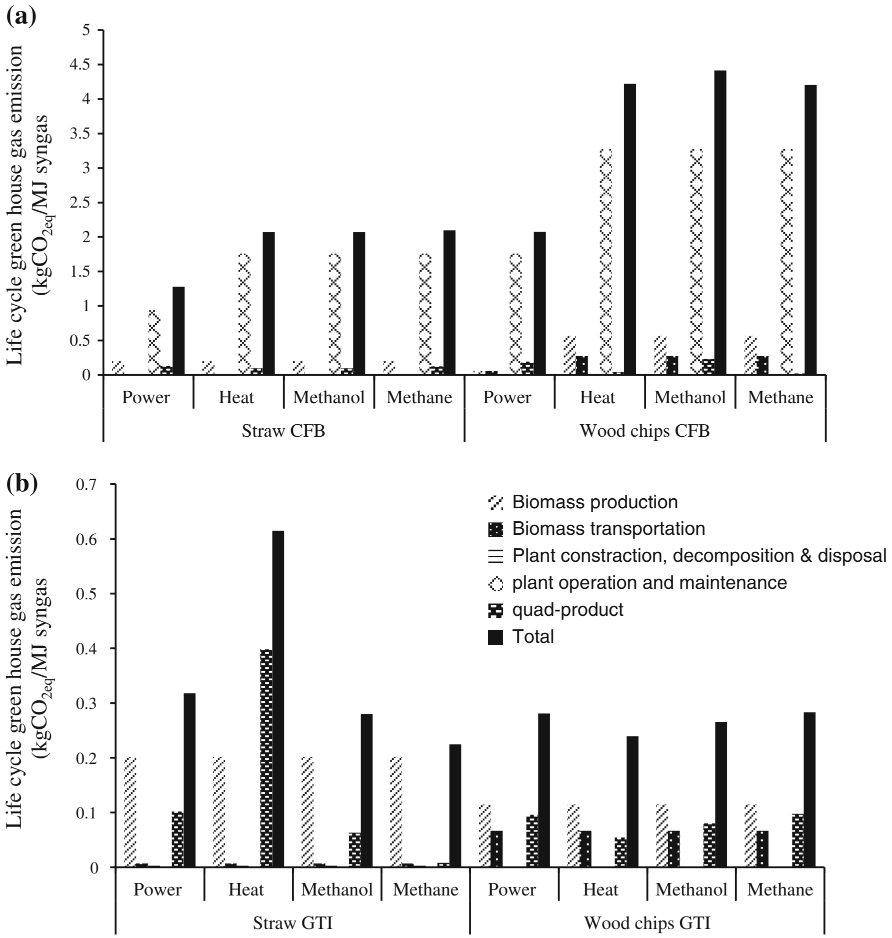

Fig. 4 Life cycle CO_2 emission from **a** CFB and **b** GTI pathways

reason for CFB wood chips pathways. Figure 5 shows the life cycle acid rain precursor emission for straw and wood chips in CFB and GTI technologies. Based on this LCA study GHG, ARP emission intensities for quad-generation production are in the range 0.24–4.41 kg CO_2eq/MJ syngas and 0.03–0.84 kg SO_2eq/MJ syngas respectively.

5.3 Sensitivity analysis

A sensitivity analysis with following scenario is carried out in this study. Scenario 1 consider excluding the farming and harvesting inputs. Hence, the feedstocks can be regarded as waste material energy need not to be allocated to feedstocks as it was in the base case. If the plant efficiency is improved from 64 to 69 % for gasification plant, scenario 2 develops for plant efficiency improvement. Scenario 3 suggests that, exclusion of silviculture and road construction from WF biomass reduces the impacts

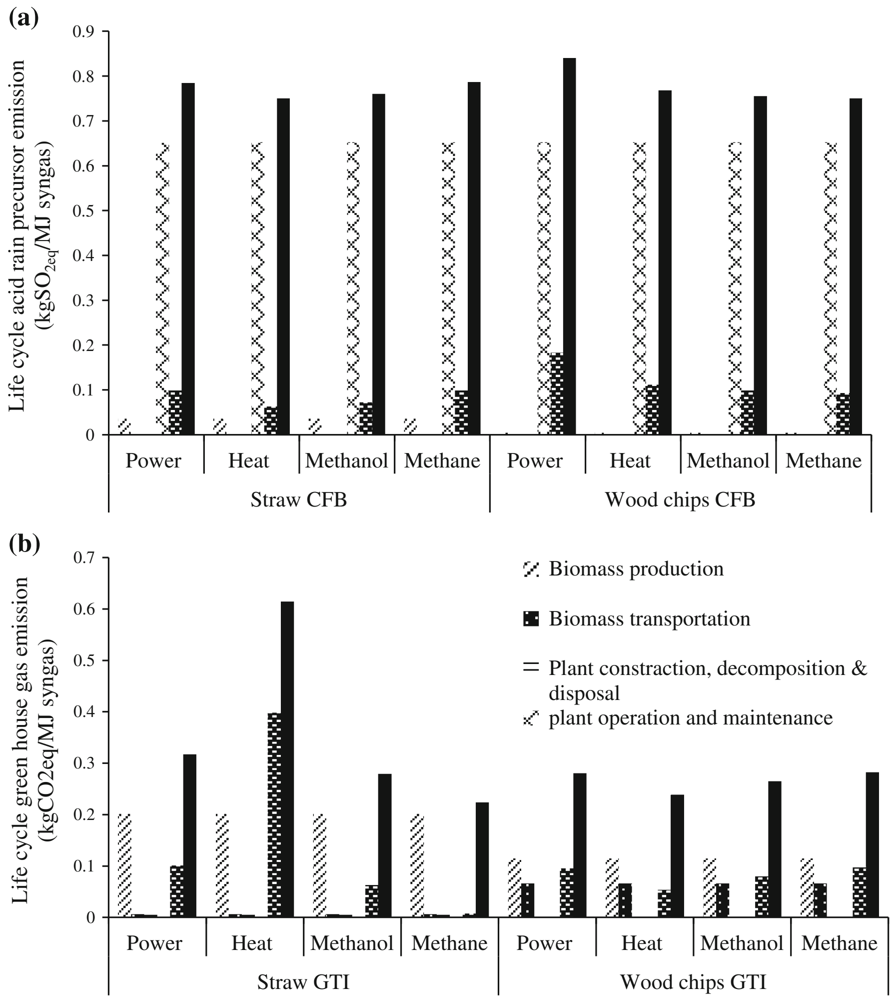

Fig. 5 Life cycle acid rain precursor emission for **a** CFB and **b** GTI pathways

significantly compared to all the pathways. Effects of 10 % increase or decrease in syngas yield is analyzed in scenario 4. This scenario is developed for both straw and wood chips. Scenario 5 consider higher operating factor for the plants (0.7 for year 1, 0.8 for year 2 and 0.95 from year 3 onwards). Based on the scenarios considered, LCA was performed again to analyze their impact. Findings have been summarized in Table 6.

5.4 Comparative study

NER for quad-production pathways is in the range of 1.3–7.2. In contrast, coal and natural gas based bio-oil production plant demonstrates NER in the range of 0.57–

Table 6 Key sensitivities and their results

Scenario	Conversion pathway syngas)	Energy (MJ/MJ case (%)	Change from base MJ syngas)	GHG (kg CO_2eq/	Change (%) MJ syngas)	ARP (kg SO_2eq/	Change (%)
(1)							
Straw	CFB	6.76	−26	1.28	−25	6.9E−01	−28
Straw	GTI	3.207	−30	0.32	−32	3.6E−02	−30
Wood chips	CFB	4.37	−17	2.07	−18	0.10	−19
Wood chips	GTI	1.26	−10	0.28	−15	7.4E−01	−13
(2)							
	CFB	1.50	−14	0.37	−19	4.7E−01	−19
	GTI	1.50	−14	0.37	−19	4.7E−01	−19
(3)							
Wood chips	CFB	4.37	−17	2.07	−16	0.10	−34
Wood chips	GTI	1.26	−10	0.28	−19	7.4E−01	−19
(4)							
	CFB	2.43	−39	0.79	34	4.9E−02	−36
	GTI	1.85	−22	0.28	19	3.6E−02	−12
(5)							
Straw	CFB	6.76	−26	1.28	−36	6.9E−01	−28
Straw	GTI	3.207	−30	0.32		3.6E−02	−30

CFB circulating fluidized bed, *GTI* Gas Technology Institute pathways

0.67 [26,41]. In case of installing quad-generation plant has a good reduction of CO_2 emissions compare to existing plant [46]. In fact, the quad-concept results in negative system-wide CO_2 emissions as a result of the replaced natural gas from sold SNG and the replaced fossil fuel in central electricity generation from sold electricity

The comparison of GHG emission from quad-generation plant and other biomass gasification is a particular way to address the question os selecting best option for policy makers. It has analyzed the wheat straw based power plant in China emits 2.9 kg CO_2eq/MJ syngas (converting MWh to MJ syngas) [47] and for quad-generation production in the range of GHG emission are 0.24–4.41 kg CO_2eq/MJ syngas.

6 Conclusions

The study is done to determine the net energy ratio and environmental advantage of using straw and wood chips for quad (power, heat, methanol and methane) production as a continuation of Denmark's quest on increasing the renewable energy penetration in its energy sector. Two conversion pathways are considered taking straw and wood chips as the sustainable energy option. Among the CFB pathways, straw based heat production pathway has maximum NER of 7.22. Similarly, among GTI pathways also, straw based methanol production pathway has maximum NER of 3.33. For CFB and GTI production pathways, use of woodchips for heat production, produces lowest GHG emission and use of woodchips for methanol production, produces less amount of acid rain precursor among the other options. By increasing the share of wind power in total energy system, reducing the use of fossil fuels use in energy production and replacement of those fossil fuels with domestic biomasses will represent the main means of GHG emissions saving in the future energy system.

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