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A CASE-STUDY ANALYSIS FOR GASIFICATION OF WOODCHIPS PRODUCED FROM FOREST MAINTENANCE

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This work aims at analyzing a complete biomass gasification chain for CHP purposes. The biomass production step is related to an existing scenario, the woodchips produced from the maintenance of the San Rossore natural park. Two different gas cleaning systems are taken into account, a wet gas clean-up and a hot gas clean-up (based on a catalytic bed with air injection for tar cracking). Performance indicators are calculated according to an inventory of the energy and mass fluxes. The results show that the most significant energy loss of the wet gas clean-up is due to syngas cooling. For the hot tar clean-up, part of the syngas sensible heat is recovered; however this is a benefit only if a suitable heat demand is available in the plant. Since part of the syngas chemical energy is lost in the catalytic bed of the hot clean-up, the overall energy efficiency of this chain is lower compared to the wet gas clean-up. The calculation shows that a hectare of forest provides fuel for the production of nearly 0.04 kWel.

1. INTRODUCTION

Biomass gasification is an option to exploit residual biomass and promote the decentralized production of combined heat and power (CHP). However, despite the simplicity of the gasification reaction, the installation and management of a gasification process require an accurate planning, involving economic, environmental, safety and process management issues. These issues are routinely addressed in an industrial context, but they may become critical when small plants in non industrial contexts are considered. Therefore case studies and technical assessment are required in order to provide information to support the development of this technology (Boukis et al. (2007), Corti and Lombardo (2004), Koroneos et al. (2007), Pantaleo et al. (2009), Rentizelas et al. (2009), Simone et al. (2009)). This work is a case study analysis referred to the use of residual biomass deriving from the maintenance of the San Rossore natural park as a fuel supply for a gasification installation. It aims at analyzing a complete biomass gasification chain for CHP purposes. Fuel, electricity, materials and utilities consumption and emissions as well as waste production are determined for each step of the chain. Finally global indicators are developed to evaluate the technical and environmental performances of the chain.

2. SCENARIO DESCRIPTION

The San Rossore natural park is located on the west border of the city of Pisa. It covers 4800 hectares; about 3000 hectares are destined to forest. The annual maintenance of the forest produces nearly 10.000 ton of wood delivered to several customers. This study considers the use of nearly 2000 ton of wood per year (the production derived from 600 hectares) as a fuel source for a 1 MWth gasification installation. According to the supply chain the harvested trees are forwarded outside of the forest and chipped. The woodchips are then delivered to the plant. The gasification plant is designed to operate 7500 hours per year, however trees cutting is performed from October to March (almost 22 weeks) to allow animals reproduction and fire prevention during spring and summer; thus there is need for woodchips storage. The gasification plant is based on a fixed-bed downdraft gasifier operated with air as gasifying agent. The raw syngas exiting the gasifier has to be cleaned to allow its

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combustion in an IC-engine. Two clean up systems (see Figure 1) are taken into account. A wet clean-up, based on the work of Sharan et al. (1997) and a hot clean-up derived from an internal design. This system includes a dolomite bed with air injection for tar cracking (based on the design of Van de Beld et al., 1997). Finally the syngas is burned in a CHP engine providing heat and electricity. The hot flue gases are used for woodchips drying.

2.1 Biomass supply

Wood harvesting is based on three phases: tree cutting by means of feller-bunchers, removal of branches and leaves operated with electric saws and finally wood forwarding to the chipping site. The wood is chipped shortly after the cutting, this practice is not the most efficient in terms of energy saving because wood seasoning helps reducing the fuel consumption (Jiris, 1995), but it is far more simple from a logistic point of view. According to the data provided from the maintenance company, the average moisture content of the wood from October to March is 45% (it is worthy to note that this data is peculiar of this specific geographical area). It is possible to assume a global consumption of 5 liters of diesel per ton of woodchips with a moisture content of 45%, a similar value related to the supply chain "road-side chipping" is reported from Wihersaari (2005a). It is assumed that the mean distance from the plant to the chipping site is 15 km, with a 25 ton load truck, the total distance covered during the year is 3512 km. The diesel consumption is taken as 0.249 Liters per Ton of wood. The total energy demand of harvesting, chipping and transportation is equal to 2.76% of the energy of the woodchips; this value is comparable to the range reported by Wihersaari (2005a). Table 1 reports the emissions collected from the SimaPro database (2009) related to this phase, these involve pollutants from diesel combustion in the engine (PM, CO, NOx) and the production of fossil CO2. The chipping process itself is also a potential source of PM and VOC, however data and emission factors are missing in the literature.

Table 1: Emission factors from Harvesting, Chipping and Transportation

Pollutant [g/ Ton_wood_45%moisture]	Harvesting & Chipping	Transportation
PM	4.60	0.05
CO	0.70	0.01
NOx	18.26	0.20
CO_2	63687.57	711.73

2.2 Biomass conditioning and storage

The wood chips delivered to the plant are a suitable fuel for the gasifier, however they have to be conditioned in terms of size (see Table 2) and moisture content (<20%) to meet the gasifier specifications. Oversized particles can lead to blockage of the solid handling equipment, while fine particles and dust are very harmful to the gasifier operation since they reduce the permeability of the gasifier bed. The screening process allows reducing the size distribution of the woodchips to the desired range. This operation causes an energy loss since the material out of specifications is rejected.

Table 2: Woodchips size distribution and gasifier specifications.

Size Class	Units	Wood Chips to the plant	Gasifier specifications
>63	mm	2.3%	oversize
8-63	mm	90.4%	88 – 100%
3.15-8	mm	4.3%	0 – 10%
<3.15	mm	3%	0 – 2%

The woodchips need to be stored for a certain time since they are produced in 22 weeks while the gasifier operates throughout the year (7500 h). During the year the woodchips are accumulated in a pile. It is assumed that during storage pile is covered with a plastic cloth. The storage period modifies the woodchips properties due to fermentation reactions producing two effects:
1) the temperature of the pile increases thus reducing the woodchips moisture content, the moisture of the pile is assumed to decrease linearly over the storage period from 45% to 27%, leading to a mean value of woodchips moisture content from the storage equal to 35%.
2) there is a loss of organic matter which reduces the energetic content of the wood chips, considered as 1% per storage month (Garstang et al., 2002).
The decomposition of the organic matter generates gaseous emissions. In particular greenhouse gases such as CH4 e N2O (Wihersaari, 2005b) are released. The woodchips degradation generates also CO2 but this neutral to the atmosphere balance since it is derived from the biomass. The emission factors for methane and nitrogen protoxide can be evaluate on the basis of the rules of thumb reported in Wihersaari (2005b) and reported in Table 3 related to the throughput of woodchips with 35% of moisture delivered to the plant. The methane and nitrogen protoxide emissions are calculated as 5% and 0.5% of the total carbon and nitrogen in the woodchips, respectively. The carbon dioxide factor is calculated as difference between the methane and nitrogen protoxide factors and the total dry matter loss.

Table 3: Emission factors for major gaseous emissions from woodchips storage.

Pollutant	[g/ Ton_wood_35%moisture]
CH_4	16685.29
N_2O	50.20
CO_2	9681.80

Prior to gasification the moisture content of the woodchips has to be reduced to suit the gasifier specifications. To this purpose a band dryer is selected. The drying medium is air mixed with the hot flue gases from the engine. The performance of the dryer is evaluated on the basis of a commercial equipment data-sheet (Scolari, 2009). Air is mixed with the hot flue gases to obtain a gas temperature of 75°C. The moisture content of the woodchips is reduced from 35% to 15%. The woodchips are then stored in a tank just before the gasifier loading system. The dryer is designed according to the maximum capability of the gasifier (nearly 1 MWth). The thermal requirement of the dryer is 45.14 kWth that is 966 MJ per Ton of woodchips with 15% moisture. The power requirement of this section of the plant (including screw conveyors, air fan, belt engine) is 96 MJel per Ton of woodchips with 15% moisture. The thermal energy is lost as steam and sensible heat. Drying is a potential source of particulate matter and VOC emissions. Nevertheless the band dryer is not likely to produce high dust levels (Brammer and Bridgwater, 1999). In addition when biomass drying is operated at low temperature is possible to avoid the release of VOC. In this case the release of condensable compounds can be ignored, since they are released above 100°C (Brammer and Bridgwater, 1999).

2.3 Biomass gasification

The downdraft gasifier performance is evaluated according to the data reported in Lettner et al. (2007) and on the basis of the experience achieved at the CRIBE research centre (Simone et al. 2011). The gasifier thermal input is 954 kWth, close to the maximum size for this technology reported in the literature (Bridgwater, 2002). The electric power requirement (loading and ash discharge systems) is 77 MJel per Ton of woodchips fed to the plant. The main assumptions are related to the tar and particulate matter productions, which are basic input data for the clean-up system. The selected values (see Table 4) are slightly higher than the average values reported in the literature (Hassler and Nussbaumer, 1999). The alkali, ammonia and hydrogen chloride emissions are selected from experimental articles (Turn, 2001; Van der Drift, 2001) so to have a reference value. The solid residues (ash with 40% carbon content) production is calculated as 0.028 Ton per Ton of woodchips fed to the plant.

Table 4: Estimation of gasifier performance parameters.

Index	Value	Source
Cold Gas Efficiency [%]	74.4	Lettner et al. 2007
LHV dry gas [MJ/Nm3]	4.5	Hassler and Nussbaumer, 1999
Gas outlet temperature [°C]	600	Lettner et al., 2007
Particulate Matter [mg/Nm3]	3861	Hassler and Nussbaumer, 1999
Tar [mg/Nm3]	2483	Hassler and Nussbaumer, 1999
Alkali [ppm_mass]	50	Turner et al., 2001
Ammonia [ppmv]	1000	Van der drift et al., 2001
Hydrogen Chloride [ppbv]	60000	Van der drift et al., 2001
Gas water content [% v/v]	14	Van der drift et al., 2001

2.4 Syngas Clean-Up and Wastewater management

The aim of two clean-up systems is to make the gas produced from the gasifier suitable for combustion in an IC-engine (see Table 5). The flow-sheet (see Figure 1) and performance of the wet gas clean-up line are based on the publications of Sharan et al. (1997) and Hasler and Nussbaumer (1999). The clean-up line consists of a cyclone for particulate matter removal, two wash towers devoted to cool the gas as well as remove tar and particulate matter and two sand filters (coarse and fine). The gas is cooled nearly to environment temperature so the sensible heat associated to the gas is lost. The system is simple and requires few inputs (water for quenching, periodic sand refreshment, electric power). This system can ensure the required removal of particulate matter but cannot safely meet the tar concentration recommended from the engine manufacturer (see Table 6) causing short engine lifetime, frequent maintenance and high engine emissions. The wastewater is highly polluted with suspended solid and tar. The suspended solids can be removed in a wastewater plant with conventional operations (settling, flotation, and filtration). Part of the tar behaves as oil so it can be removed by flotation, the addition of active carbon, as already mentioned, is meant to reduce the presence of organic compounds which are not readily biodegradable (e.g. PAH). Figure 1 reports the flow-sheet of the hot gas clean-up, the data related to this clean-up are based on our design. The gas from the gasifier enters a cyclone for particulate matter removal, and subsequently a “reverse flow” dolomite bed. This technology was developed by Van de Beld et al. (1997) and it is based on a periodical inversion of the gas flux in the bed to allow for the recovery of the heat of reaction. The dolomite bed is fed with air which burns a certain amount of gas to increase the temperature to 1000°C and promote tar cracking reactions, thus reducing the gas LHV. The amount of gas to be burned is calculated assuming that the gas must be heated up from 850°C to 1000°C, with a gas outlet temperature of 760°C. The tar removal efficiency is taken from Van de Beld et al. (1997).

The hot clean-up is composed as follows: alkali getter (Turn et al., 2001), ceramic filter, thermal recovery in a heat exchanger-condenser, batch water wash tower, batch wash tower with sulphuric acid solution. The hot clean-up line is likely to upgrade the gas to the engine specifications. The hot clean-up line needs water for alkali getter regeneration and wash towers and allows recovering some of sensible heat of the gas from the gasifier. This heat source can be used to heat up air to dry an additional quantity of woodchips, thus saving methane or other fuels. Water from alkali getter regeneration, heat exchanger condensate and water from the first wash tower is delivered to a biological treatment.

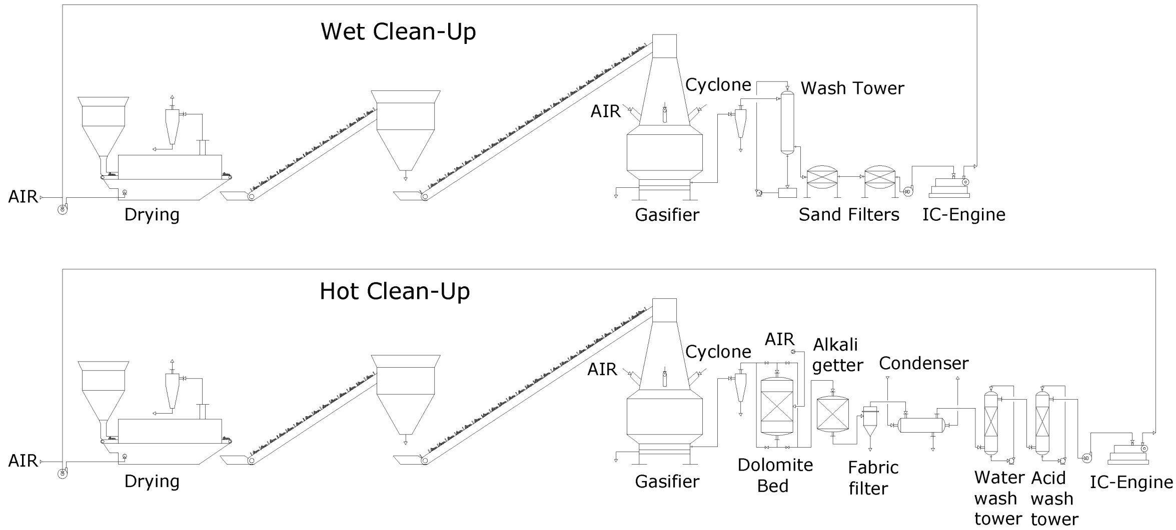

Fig. 1: flow-sheets of the two gasification plants.

Table 5: Engine specifications for the use of gas from biomass gasification.

Parameter	**Value**	**Source**
Particulate matter	< 50 mg/m3	Hassler and Nussbaumer (1999) ; Lettner et al. (2007)
Particle size	< 10 micron < 3 micron	Hassler and Nussbaumer (1999) ; Lettner et al. (2007)
Tar	< 50 mg/m3 < 100 mg/m3	Hassler and Nussbaumer (1999) ; Lettner et al. (2007)
Ammonia	< 5.5 mg/kWh	Lettner et al. (2007)
Halogen compounds	< 10 mg/kWh	Lettner et al. (2007)
Sulfur	< 200 mg/kWh	Lettner et al. (2007)
Temperature	30-40 °C	Lettner et al. (2007);

Table 6: Clean-up line performances.

Clean-Up Performance Index	Hot	Wet
Tar removal efficiency [%]	98.55	96.1
Particulate removal efficiency [%]	99.88	99.9
Tar concentration to the engine [mg/Nm3]	36.06	100
Particulate matter concentration to the engine [mg/Nm3]	7.21	5

2.5 Power generation

The gas from the clean-up section is burned in a CHP engine for the production of electric power and heat as water at 90°C. The heat associated with the hot flue gases is used to dry the woodchips entering the plant by mixing them with air to reach 75°C and the desired water vapor concentration. The engine performance was evaluated by comparing scientific articles and data-sheet about the use of gas from gasification in IC-Engine (Baratieri et al. 2009, Sridhar et al. , 2001) the estimated parameter are reported in Table 7.

The emission factors are taken from CAEMA (2009) and compared to the work of Sridhar et al. (2001). The NOx emissions are comparable as well as the Particulate Matter (PM), whilst the CO concentration seems to be underestimated. No references were found for emission factors related to unburned hydrocarbons. As far as the gas clean-up is concerned the engine has to be equipped with a catalytic oxidation unit, whilst there is no need for a SCR unit. It is worthy to note that the emission factors of the wet gas clean-up engine should increased as a consequence of the high tar level to the engine, however due to the lack of reliable data this difference is neglected. The engine power self consumption is evaluated from data sheet of commercial equipments equal to 0.012 MJel per MJel of electrical power produced. Table 8 shows the results of the mass and energy balances related to the two engines. Both the two systems produce enough flue gas to provide heat for the incoming woodchips.

Table 7: Engine parameters.

Parameter	Value
Electric yield [%]	30
Thermal yield (hot water) [%]	35.3
Flue gas yield (flue gas) [%]	24.7
Losses [%]	9
Emission CO [mg/Nm3]	324
Emission PM [mg/Nm3]	2.7
Emission NOx [mg/Nm3]	378
Power production [MJel/MJel]	1
Hot water 90°C [MJth/MJel]	1.18
Flue gas [MJth/MJel]	0.82
Losses [MJth/MJel]	0.33
Air excess [%] (Sridhar et al. 2001)	15%

Table 8: Engine emissions and performance data from material balance.

Parameter	Hot Clean-Up	Wet Clean-Up
CO [Ton/MJel]	$4.39*10^{-7}$	5.158E-7
PM [Ton/MJel]	$3.66*10^{-9}$	4.298E-9
NOx [Ton/MJel]	$5.12*10^{-7}$	6.018E-7
Flue gas temperature [°C]	450°C	425°C

3. PERFORMANCE INDICATORS AND DISCUSSION

The two gasification chains are based on different gas clean-up systems, which influence the energetic output of the gasification plant and the global performance of the chains. The hot gas clean-up is more complex than the wet gas clean-up and it is likely to be more expensive from an economic point of view (especially in relation to the plant size). Vice-versa the hot clean-up maintenance operations seem to be safer than the wet clean-up. Figure 2 shows the Sankey diagrams of the two chains. Table 9 reports the values of some performance indicators adopted in the analysis. Prior to gasification two energy losses occur due to the rejection of out of size chips and organic matter losses due to fermentation during the storage period. These losses are 5% and 3.8% of the original energy associated to the harvested biomass. Gasification itself causes an additional energy loss (5.9%) due to thermal dispersion and unconverted organic material. In the case of wet clean-up the cooling of syngas is the main energy loss (17%). In the case of hot clean-up the energy loss (3.9%) is due to partial oxidation of the syngas in the dolomite bed to reach the temperature required for tar cracking, however the syngas must be cooled to nearly 40°C in order to be used in a IC-Engine, so the sensible heat of the gas is transferred to an air stream. This heat stream (16.1% of the initial energy) doubles the available heat for drying per MJel produced, compared to the wet clean-up (see Table 9). Therefore the availability of a heat demand is a key issue in determining the performance of this clean-up system. It is worthy to note that the performance of the two systems depends on the tar output from the gasifier. The wet clean-up causes the loss of all the chemical energy associated to tar, so the higher the tar content the higher the energy loss due to syngas cleaning. The hot clean-up converts tar into combustible species so this system allows saving the chemical energy retained in the tar. In this work typical medium-high tar content in the raw syngas was considered (see Table 4). In this condition the hot gas clean-up leads to lower efficiency in terms of electrical energy production (19.8% VS 20.5%, or in other terms 9304 VS 9634 MJel per ha of forest). As a consequence the electrical and fuel demands of the chain have a higher impact related to main output, as reported in Table 9 and Figure 3.

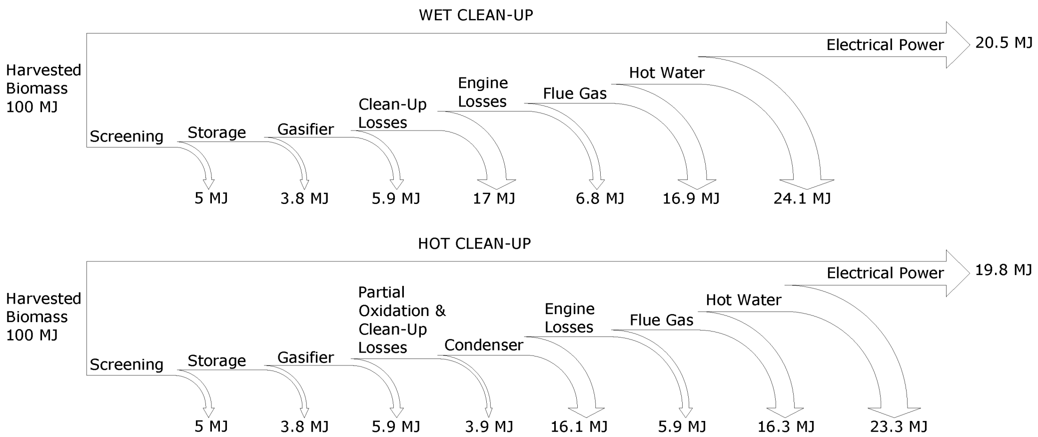

Fig. 2: Sankey diagrams of the two gasification chains.

Table 9: Performance Indicators

Index	Electrical power yield	Heat yield	Wastewater production	Electrical demand	Fuel demand	Thermal recovery
Unit	%[Jel/Jw]	%[Jth/Jw]	[g/Jel]	%[Jel/Jel]	%[Jth/Jel]	%[Jth/Jel]
Hot	19.8%	23.3%	8e-5	19.1%	9.8%	42%
Wet	20.5%	24.1%	9e-5	17.1%	9.5%	21%

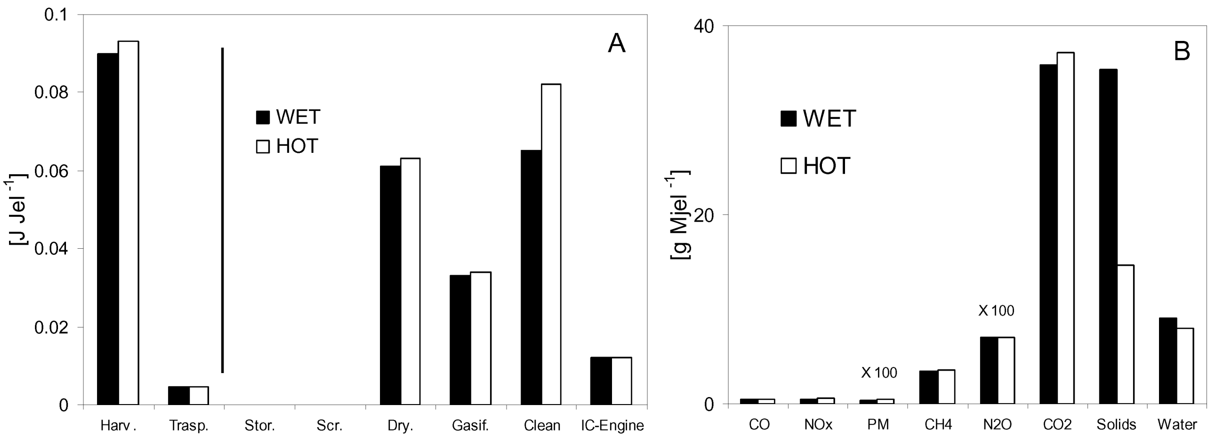

Fig. 3:(A) fuel and power demands and (B) emissions of the two plants per MJ of electrical power produced,

The main fuel demand is due to biomass production and transportation to the plant (nearly 2.8% of the initial energy content of the biomass). Waste transportation (not reported in Figure 3A) can be a significant fuel demand when the distance approaches 50 km and becomes comparable to harvesting when the total distance reaches 300 km. The power requirement of the hot clean-up is higher due the more complex flow-sheet. Drying involves a large consumption of power, therefore using biomass with very low moisture content (for instance pine nuts) increase the net power production of the plant. Table 9 reports the wastewater and emission productions for the two plants. Wastewater is most significant residue from this plant; the hot clean-up allows reducing the amount of wastewater from the plant (8e-5 VS 9e-5 Ton wastewater per MJel produced). However since the more than half of the water generated from the clean-up line derives from condensation of water vapor contained in the syngas, the hot syngas clean-up plant must deal with a considerable amount of wastewater as well. The real benefit of the hot clean-up is that the expected pollution level is lower than that of wet clean-up, so there is no need for a pre-treatment of the raw wastewater (for instance active carbon and flotation) prior to the biological treatment. In addition a higher engine life-time can be expected. The lower global efficiency of the hot clean-up chain leads to higher emissions of combustion by-products due the lower conversion of the wood chemical energy into electrical power (see Figure 3B). The main disadvantage of the wet clean-up is high production of solid wastes due to frequent substitution of the sand filters. It is worthy to note that this analysis cannot evaluate all the environmental aspect of the chain since do not involve side-effects in treating and disposing such residues. The typical combustion emissions derive from the syngas combustion in the engine, the contribution of the harvesting and transport stage are almost negligible, therefore it is expected that even when the mean distance from the plant is increased there is not a big change in the total emissions and it seems that the higher the size of the plant the lower the impact of harvesting and transport. However harvesting and transport are responsible for the total CO2 emitted from the chain. Considering the storage as an active process spread the range of emissions to CH4 and N2O, this is somewhat important since these gases have a higher green house gas potential than CO2. Finally it is worthy to note that part the charcoal derived from the gasifier can be delivered to different destinations (according to the local legislation). It can be regarded as a waste, which has to be disposed as a special residue, or it can be considered a fuel, thus allowing for some energy saving, or finally it can be used as a solid amendant, returning some CO2 directly to soil and reducing the total CO2 emitted and lowering the greenhouse potential of the chain. As mentioned before the flue gases produced from the engine can be used as heating medium in the drying system, this allow saving some energy and increase the overall efficiency of the chain. Other potential sources of heat are woodchips rejected by the screening and the vegetal charcoal produced from the gasifier. The combustion of these by-products allows for the production of additional heat. Furthermore additional heat can be derived from the cooling of the syngas in the clean-up. Figure 4 shows that the flue gases are fairly enough to satisfy the request of the gasifier self supply and there is a large amount of excess heat to be allocated. Therefore it is fundamental to identify a suitable heat demand to enhance the energy and environmental performance of the plant. Drying additional quantities of woodchips or producing wood pellets for other facilities could be suitable options to exploit the heat excess. On the other it must be noted that the higher the integration the higher the complexity within the plant, for instance in terms of management, ancillary equipment and maintenance planning.

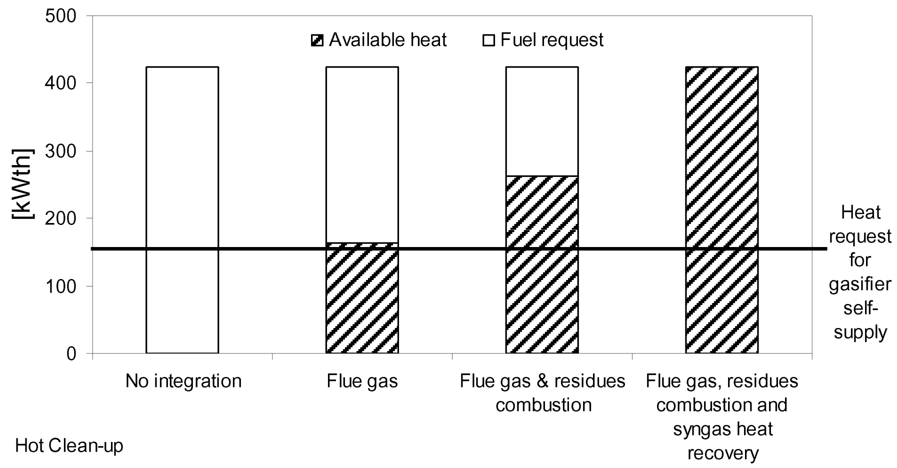

Fig. 4: heat availability with different management of the heat and material streams

4. CONCLUSIONS

It was highlighted that all the steps of the chain require a proper investigation in order to carry out a global assessment. For instance considering storage as an active process takes into account the loss of some energy retained in the biomass and the production of greenhouse gases such as methane and nitrogen protoxide. The analysis pointed out that the use of a hot clean-up seems to lead to little benefits, except for the reduction of solid wastes and wastewater. However it is worthy to note this kind of analysis does not take into account possible difficulties and collateral problems associated to the treatment and disposals of such wastes. The overall energy efficiency and therefore environmental suitability of the chain depends on the plant integration and available heat demands. One important result for future comparison with different conversion chain is that with this route it is possible to achieve nearly 0.04 kWel per hectare of forest. It is believed that this kind of assessment can be a useful basis for further work based on LCA.

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