Comparative Life Cycle Assessment (LCA) of Construction and Demolition (C&D) Derived Biomass and US Northeast Forest Residuals Gasification for Electricity Production

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Comparative Life Cycle Assessment (LCA) of Construction and Demolition (C&D) Derived Biomass and US Northeast Forest Residuals Gasification for Electricity Production

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ABSTRACT With the goal to move society towards less reliance on fossil fuels and the mitigation of climate change, there is increasing interest and investment in the bioenergy sector. However, current bioenergy growth patterns may, in the long term, only be met through an expansion of global arable land at the expense of natural ecosystems and in competition with the food-sector. Increasing thermal energy recovery from solid waste reduces dependence on fossil- and bio-based energy production while enhancing landfill diversion. Using inventory data from pilot processes, this work assesses the cradle-to-gate environmental burdens of plasma gasification as a route capable of transforming construction & demolition derived biomass (CDDB) and forest residues into electricity. Results indicate that the environmental burdens associated with CDDB and forest residue gasification may be similar to conventional electricity generation. Land occupation is lowest when CDDB is used. Environmental impacts are to a large extent due to coal co-gasified, coke used as gasifier bed material, and fuel oil co-combusted in

the steam boiler. However, uncertainties associated with preliminary system designs may be large, particularly the heat loss associated with pilot scale data resulting in overall low efficiencies of energy conversion to electricity; a sensitivity analysis assesses these uncertainties in further detail.

KEYWORDS Life Cycle Assessment (LCA), Plasma Gasification, Waste Management, Construction & Demolition Waste, Forest Biomass, Electricity Production

INTRODUCTION

Renewable energy is expected to contribute towards sustainable development and reduce impacts in particular related to global climate change. By 2007, at least 64 countries around the world had set a national target for the share of renewables in their energy mix (1). In this context, biomass for energy and liquid fuels production is considered as an alternative to fossil-based energy systems by countries worldwide. In 2007, biomass provided about 45 ± 10 EJ to global final energy consumption (out of a global total of 388 EJ per year), therefore being the largest renewable energy source used (2). However, the majority of bioenergy is currently due to traditional biomass use such as cooking and heating, particularly in rural areas of the developing world (3). In contrast, commercial energy production from biomass for industry, biofuels, and power generation represents a lower but still significant share (some 7 EJ per year in 2000 out of a total of 56 EJ in year 2000) (2).

Biomass power contributed a total of 1.25% (does not include waste-to-energy capacity from municipal solid waste (MSW)) to the global total power generation capacity of 4950 GW in 2010 (3). In the United States, most biomass electricity comes from wood and agricultural residues as well as black liquor burned during cogeneration by industry. It is expected that total global primary energy demand in 2050 could reach between 800 and 1,400 EJ (2). The estimated global potential for bioenergy production is estimated to be between 200-400 EJ (2).

In view of current efforts to increase commercial bioenergy supplies, the availability of global arable land for non-food purposes requires special attention. The current growth in bioenergy production may in the long term only be met through an expansion of global arable land at the expense of natural ecosystems and in direct competition with the food-sector (1,4,5). Against this background, the use of waste and production residues for bioenergy production is gaining increased interest as an alternative to the use of virgin greenwood biomass (1).

Waste as bioenergy feedstock. Various types of organic waste including (a) agriculture and forestry residues and (b) municipal and industrial wastes (i.e. biodegradable municipal solid waste, plastic waste, construction and demolition (C&D) waste, and sewage sludge) are considered as potential feedstock for bioenergy and chemicals production (1,6–8). Removing agriculture and forestry residues from nature may present problems as these maintain soil fertility and soil carbon content, and further research is required to determine the amount that can be utilized (1). Therefore, technologies capable of utilizing existing municipal and industrial organic wastes for energy recovery will be of particular interest.

In 2003, the United States generated an estimated 154 million metric tons of C&D debris of which about 48% was recovered (9). The wood fraction of C&D debris is a key component for recycling as a feedstock for thermochemical conversion. The amount of wood in C&D debris was found to average 31.5%, ranging from 20.2 to 45.3% in various states of the U.S. (10). Pressure treated wood averaged 1.6% of all C&D waste, while high grade wood consisting of pallets and crates and other unpainted wood made up 11.5% of all C&D waste. Besides high grade wood, requiring little pre-treatment prior to thermochemical treatment, also painted/stained wood (6.5%), engineered wood (8.1%), wood furniture (0.3%), and other wood (6.0%) may be used for energy recovery.

In the Northeastern (NE) United States, the Northeast Waste Management Official's Association (NEWMOA) estimates that in 2006 approximately 11 million metric tons of C&D waste were generated (11). Of this about 9 million tons was sent to landfills, with 70% of the total estimated C&D waste generated disposed as C&D waste and 13% used as alternative daily cover in landfills. Landfilling takes place despite the fact that several alternative options for the management of C&D derived wood exist or are being developed. These include 'well-established' technologies such as biomass boilers and particle board manufacturing, as well as more novel conversion routes including gasification and pyrolysis, and cellulose ethanol production facilities (10). However, the introduction of latter technologies to the U.S. market has been slow. Reasons for this include but are not limited to (a) uncertainty on the regulatory side as to how new waste conversion facilities should be permitted, (b) inconsistencies in the eligibility of renewable energy credits for power sale, and (c) high installation costs (12,6). A recent study investigates the life-cycle wide environmental burdens of various traditional end-of-life management options for C&D wood (i.e. combustion, landfilling, and recycling) in New Hampshire (13).

A study by Buchholz et al. (14) estimates that in the NE U.S., biomass production for energy use may range from 13.7 – 15.8 million metric tons of biomass per year (assuming diversion of current pulp harvest to bioenergy and increased harvest rates) or 4.2 – 6.3 million metric tons per year (excluding current biomass from pulp harvest), therefore representing another potential feedstock source.

Waste-to-energy systems. Besides commonly used waste incinerators for energy generation, gasification and pyrolysis allow the production of a syngas that can be used for the generation of electricity or alternatively as a feedstock for the production of fuels and chemicals via various catalytic conversion routes (4). The treatment of waste feedstock via gasification and pyrolysis is still a relatively novel waste management practice. However, both pyrolysis and gasification have been well regarded for their potential production of useful products from various types of organic waste, as well as for generating less air emissions and residues than conventional waste incineration technologies (15,16).

Among the various gasification technologies for solid waste treatment (see e.g. (17)), *plasma arc gasification* is seen as a commercially viable option (18). Plasma gasification is a high-temperature process in which the carbon-based materials of the organic waste stream are converted into syngas (CO and H2), and inorganics produce a glass-like vitrified slag. The high temperature needed to produce the plasma is provided by an electric arch in a torch using electricity. The plasma gasification reactor is typically operated between 3980 to 6980°C (18). In commercial operations, carbonaceous material such as coal or coke is added to the gasification feed to absorb and retain heat from the plasma torches and provide the conditions for melting inorganics (19). To date, information on the life-cycle wide environmental burdens of waste-to-energy routes applying plasma gasification is limited.

EXPERIMENTAL SECTION

Goal and system boundary. Against this background, the *goal of this study* is to assess the system-wide environmental burdens of using plasma arc gasification in the NE United States for the production of electric power from feedstock mixes consisting of 1.) C&D derived biomass

(CDDB), 2.) forest residues, and 3.) bituminous coal. The aim of including different feedstock combinations in the analysis is to examine the flexibility of the gasifier to deal with mixes of homogenous (forest residuals and coal) and heterogeneous (CDDB) inputs. CDDB is of special interest as it represents a feedstock source potentially available from currently existing waste management schemes in the NE U.S. that would not require additional forest or arable land for its provision (see introductory remarks). The primary function of the plasma gasifier is to produce electric power, and hence we compare the use of varying feedstocks on the basis of a functional unit of 1 kWh of electricity at the factory gate. Results are furthermore compared to conventional electricity production (i.e. U.S. average power grid and NE U.S. power grid (both in line with the geographical scope of the study), as well as coal-fired power (widely known reference). The research method used in this study is life cycle assessment (LCA). Inventory data are obtained from direct communications with our company partner and various technical reports. Technologies included are currently existing processes such as pilot-plant plasma gasification, syngas clean-up systems, boiler and steam turbine, as well as conventional forest harvest and C&D waste sorting and processing systems. The modeled gasification and electricity generation process is located in the NE United States. An LCA model following the ISO 14040 and 14044 standards (20,21) is developed using SimaPro 7.3 software. Figure 1 shows the major stages of the product systems, which were investigated as unit processes.

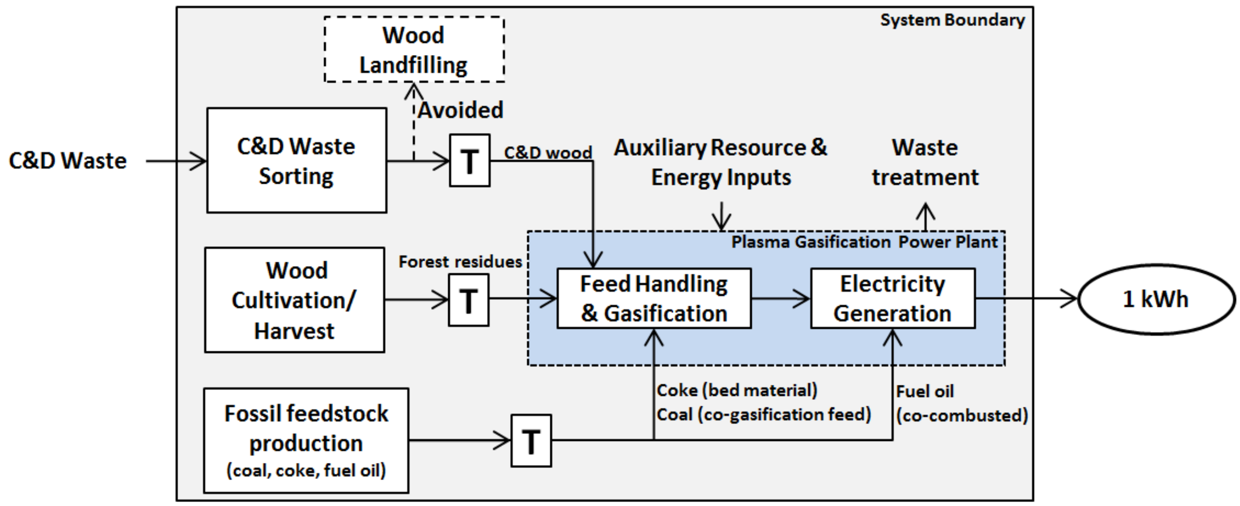

Figure 1. System boundary of the plasma gasification system under study. T = Transport

The system under consideration includes sorting of the *C&D waste* in a materials recovery facility (MRF) to obtain the wood fraction, transportation to the plasma arc gasification plant, feed handling and gasification, syngas clean-up and subsequent electricity generation via combustion in a boiler/steam turbine. It is assumed that C&D debris is a waste that requires disposal or alternative uses and that waste collection take place because it is a regulatory requirement or economically feasible due to the value of recovered material. The environmental implications of the process that generated the C&D debris as well as waste collection were therefore excluded from the life-cycle analyzed. We assume that CDDB utilized in the NE United States would be diverted from landfills (under current practices about 83% of all C&D wood generated in the NE U.S. is landfilled (11)) and hence credit the system with the avoided environmental burdens associated with waste wood landfilling (system expansion). This is accounting for the fact that, if not diverted to the gasification system for electricity production, CDDB will require safe disposal (currently landfilling) while electricity will be supplied via other routes. We test this assumption in the sensitivity analysis by excluding system expansion from the analysis.

The life cycle of *forest biomass* includes tree cultivation & harvest, transportation, feed handling and gasification, and subsequent electricity generation via combustion in a boiler/steam turbine. It is assumed that primary wood residues from commercial logging operations are used as feedstock to the gasifier.

Among the major differences between C&D waste and NE forest residue utilization are wood growth and harvest, avoided landfilling, as well as the transport distance (using pilot plant data we assume that CDDB would be available within a 35 miles radius of the gasification power plant, while forest residues would come from within a 70 miles radius). The shorter transportation distance accounts for the fact that C&D waste processing stations would typically be located in closer proximity to conversion plants than forest biomass.

Life-cycle inventory data. The life cycle inventories (LCIs) compiled for C&D waste, forest biomass, and coal gasification are sourced from various reports and direct communications with our company partner. We use a combination of pilot plant data (based on actual test runs) and computer simulation data (based on a heat and mass balance computer program developed by the industry partner) for the plasma gasification reactor (PGR), and data from confidential design reports as well as publicly available data to model the syngas cleanup system and subsequent electricity generation. The goal of including outputs from computer simulations together with pilot plant data is to illustrate how a commercial PGR might perform in the future. Resource, material and energy inputs were linked to conventional LCI databases including U.S. LCI (22) and Ecoinvent (23) and all data fed into the LCA software SimaPro 7.3 (see SI: Table 1).

With the exception of short rotation forestry, **forest biomass** represents the prevalent source for wood-based fuels (24). In the NE U.S., the primary outputs of forest harvest are sawlogs, pulpwood, and bark as well as stumps and primary residues, typically left in the forests to decay (25). For this study, we assume that *primary residues* (logging residues excluding stumps) are utilized as feedstock for plasma gasification. According to Buchholz et al. (14), 77% of current forest biomass removals in the NE represents the merchantable fraction (i.e. sawlogs, pulpwood, and bark), while 4% of it is present in non-usable stumps (left in the forest), and the remainder (19%) represents primary residues such as tops and logging residues (currently left in the forest) that could be diverted to the plasma gasification plant. It should be noted that even though the use of primary wood residuals would not cause any consequential effects due to diversion and competition with other uses (e.g. pulp), it could still have adverse effects on the *forest habitat* (biodiversity) and *soil nutrient fertility*, especially if carried out on large scales. One way to counteract nutrient transport away from forests may be to recycle the wood ash from bioenergy plants, thereby compensating for nutrient loss (24). However, this is outside the goal of our analysis and not further investigated. For our analysis, inventory data on traditional tree growth and harvest in the NE U.S. and related fuel and lubricant inputs comes from refs (22,25). Natural regeneration is assumed and life-cycle stages include stand establishment, tree harvest, transport of whole trees, delimbing, and loading of the wood onto a truck (22). Atmospheric CO_2 assimilation is based on the carbon content of wood fractions. Environmental burdens due to fuel and lubricant use as well as land occupation are allocated based on the dry volume of product outputs using the percentages stated above. The Consortium for Research on Renewable Materials (CORRIM) (25) simulated three different forest management scenarios for softwood and hardwood growth/harvest (low, medium, high). We use the medium management intensity level in our LCA model and assume primary residues consisting of equal amounts of hard- and softwood are diverted to the power plant. Land occupation estimates per cubic meter of wood are based on typical hardwood and softwood yields per year and rotation cycles published by CORRIM (25). Ecoinvent data (26) is used to obtain estimates of land occupied by the building of roads for forest access. Land occupation in the NE forests equals 2.73 and 4.05 m^3/ha yr for hardwood and softwood respectively. This is close to the U.S. forest average net annual increment (representing the average annual volume over a reference period of gross increment less natural losses) of 3.64 m^3/ha yr (27). Finally, forest residues are chipped in a mobile chipper prior to transportation to the conversion plant (26). The final product is 1 m^3 mixed softwood/hardwood chips from primary residues with a density of 480 kg/m^3 (dry weight). The average energy content of forest biomass (as received) is 17.31 MJ/kg. Water content varies between 12-26% and is taken from respective test reports of our industry partner.

The electricity (20.3 kWh/metric ton mixed C&D waste) and fuel inputs (2.4 L diesel fuel/metric ton mixed C&D waste) associated with mixed **C&D waste** in a MRF are taken from Levis (28). Electricity inputs are modeled using fuel shares for the U.S. NE power grid (NEPOOL) (29) and linking them to Ecoinvent (23) and U.S. LCI (22) unit processes. Fuel inputs are modeled using U.S. LCI data for diesel fuel. Allocation of fuel and energy inputs is based on the 'as received' weight of the components sorted (dirt/fines 25%, bricks 5%, concrete 10%, asphalt 6%, corrugated cardboard 7%, ferrous metals 3%, non-ferrous 2%, gypsum wallboard 8%, CDDB 22%, miscellaneous 12%). CDDB obtained is assumed to be pre-processed to a size that can be fed directly into the plasma gasification reactors (PGRs). The average energy content of CDDB (as received) is 10.65 MJ/kg. Water content varies between 16-

30%. Feedstock transport is modeled using generic data for a diesel powered combination truck (22).

Data for the unit processes of the plasma gasification power plant (see TOC Art) are based on confidential test and design reports (30–33). For the pilot **plasma gasification** plant, four separate refractory-lined plasma torch air blown gasifiers operating under high temperature and atmospheric pressure are to be used to thermally convert CDDB, forest residues, and coal into syngas. The commercial facility is envisaged to operate with six 600 kW plasma torches. Ash and other inorganic materials present in the feedstock are melted down and flow to the bottom of the PGR forming a slag. The slag (typically 1-5% by weight of feedstock input) exits the gasifier separately from the syngas and is removed from the process by the slag handling system. Gasifiers are designed to operate with metallurgical coke or anthracite (on average 0.063 kg per kWh). Because of the ash content of the coal, wood chips and coke mixture, flux material (limestone/sandstone) is required to maintain the proper slag basicity. We obtained energy and material balances for *pilot plant runs* in which forest residues and CDDB (100%), as well as combinations of coal with both feedstocks, was gasified from confidential test reports (Table 1) (32,33). In addition, plasma heat and material balances for *commercial systems* based on computer model runs were provided (Table 1) (31).

Feedstock mix	Name	Type of Data
Forest biomass (100%)	1-Bio	Pilot plant
CDDB (100%)	2-CDDB	Pilot plant
Forest biomass (44%) / CDDB (56%)	5-Bio/CDDB	Pilot plant
CDDB (65%) / Forest Biomass (35%)	7-CDDB/Bio*	Computer simulation
Coal (38%) / Forest biomass (62%)	3-Coal/Bio	Pilot plant
Coal (33%) / CDDB (67%)	4-Coal/CDDB	Pilot plant
Coal (53%) / Forest Biomass (47%)	6-Coal/Bio*	Computer simulation

Table 1 Various gasifier feedstocks investigated. Percentages indicate percentage by mass of the feedstock. * PGR based on computer simulation data provided by (31).

The pilot plant is only about 1/5 the size of a commercial PGR with higher heat losses due to a limited amount of refractory lining and water wall cooling system. This is reflected in higher coke consumption and lower overall conversion efficiencies. Torch power inputs equal about 2.8% (as percentage of total energy input), while electricity requirements for feed processing (conveyor) and other auxiliary equipment are 0.017 kWh/kg feed (30) and 0.100 kWh/kg feed (34), respectively. The PGR produces raw syngas (sent to subsequent syngas cleaning), heat (recovered via HRSG and used internally in the gasifier), slag (co-product), and small amounts of ash (landfilled). According to plant operators, slag produced can be used as roadbed aggregate or alternative daily cover in landfills. However, due to a lack of detailed data we assume that the beneficial use opportunities between slag co-produced are similar for the different feedstocks and they are therefore removed from the assessment (we investigate potential landfilling of slag in the sensitivity analysis). Based on information provided by the industry partner, average transport distances to the NE region are 580 miles (coal from Pittsburgh), 350 miles (coke/anthracite from Pennsylvania), and 150 miles (limestone/sandstone).

Syngas cleanup consists of particulate removal using bag filters to remove fly ash from the raw syngas and two primary water scrubbers using water sprays to quench the syngas, condense particulate aerosols and help to remove fine solids and trace components not captured in the bag filter. Two final polishing wet scrubbers further condense aerosols and capture any residual acid gases, filterable and condensable particulate not captured in the primary system. It is assumed that due to quenching of the high-temperature syngas, roughly 0.400 kWh per kg waste are lost (34). Solids removed are led into the slag handling system. Wastewater (0.031 kg per kg syngas) is discharged to a sump and treated in a conventional wastewater treatment plant. Mercury present in the feedstock is vaporized in the PGR. Activated carbon filters consisting of two static carbon filter beds in series are used to remove mercury from the syngas. Carbon filters, once mercury saturated, are disposed in a regulated hazardous waste landfill. Mercury emission rates come from respective test reports. Data on other potential metal contaminants (e.g. chromium lead, arsenic) to air, soil, and water was not available. As a result we do not investigate toxicological and human health impacts in the LCA study. Sulfur in the feedstock is mainly converted to hydrogen sulfide (H_2S) during gasification. H_2S is removed from the syngas stream via bio-desulphurization using the *Shell Paques* technology (30,35,36). Sodium hydroxide inputs equal roughly 0.020 kg and water inputs 0.610 kg per kg syngas. About 99.8% of all H_2S present in the raw syngas is removed during this step and elemental sulfur generated (30). No specific data on the type of beneficial use of elemental sulfur was available and hence the co-product excluded from the assessment.

Power generation takes place by combusting 90% cleaned syngas together with 10% No. 6 oil (by heat input) in a boiler, with steam generated powering a steam turbine for electricity production (30). The boiler/steam turbine operates at an efficiency, expressed as useful energy output divided by total energy input, of 34.8%. Gross electricity generated at the steam turbine is used to supply internal power requirements (torch power, auxiliary equipment) first with excess available for external sale (net electricity). During the combustion of syngas and fuel oil in the boiler, flue gas is generated which is discharged via the stack of the power plant. Fossil and biogenic CO_2 emissions associated with the generation of 1 kWh of electricity are calculated based on ref (37) using the following equation:

$$E = A_{f,m,} \cdot F_{c,m} \cdot F_{ox} \cdot \left({}^{44}/_{12} \right) ,$$

Where E = Mass emissions of CO_2 (kg), $A_{f,m}$ = Mass of fuel consumed (kg), $F_{c,m}$ = Carbon content of fuel on a mass basis (kg C/kg feedstock), F_{ox} = Oxidation factor to account for the fraction of carbon in the fuel that remains as soot or ash, and (44/12) = Ratio of the molecular weight of CO_2 to that of carbon. Fossil CO_2 emissions from coal (0.76 kg C/kg) (33), coke/anthracite (0.58-0.70 kg C/kg) (38), and No.6 oil (0.85 kgC/kg) (39) were calculated assuming oxidation factors of 1. Biogenic CO_2 is based on carbon contents from refs (32,33). Syngas combustion leads to further air emissions including small amounts of particulate matter, hydrogen chloride, hydrogen fluoride, sulfur dioxide, and nitrogen oxides. While air emissions of mercury and hydrogen sulfide are based on inventories provided by our industry partner, due to a lack of detailed emissions data it was decided to complement the LCI with emissions data from the Plasco gasification process (34).

System expansion. Organic waste landfilled partially degrades under anaerobic conditions of a landfill and forms methane (a potent greenhouse gas) as well as leachate. Potential environmental benefits of waste wood diversion from landfills are modeled using data on typical waste wood disposal from Doka (40). According to this data about 0.065 kg CO_2-eq per kg wood are avoided if waste wood is diverted to other uses (23). This is due to the low overall degradability (0 – 3.2%) of wood waste during 100 years (40).

Biogenic carbon accounting. In recent years, the carbon neutrality presumption of biomass feedstock in LCA has been challenged (41,42) as indirect emissions of land use change (1) and the dynamics of forest carbon flows over time (43,44) are receiving increased attention. For this study, collecting forest residues for bioenergy production results in short-term emissions of carbon stored in the feedstock as compared to long-term decomposition in the forest. The difference between current practices (decay of residuals left in the forest) and feedstock diversion to the gasification plant (syngas combustion) is the time-frame over which these emissions occur (assuming complete decay of forest residuals to CO_2). Ideally this would be included using a forest-carbon model such as FORCARB2 (45). However, this is outside of the scope of the current assessment. Instead we give *implicit sequestration* credits (42), presuming a net flux of biogenic carbon of zero but report biogenic carbon stock changes (due to harvest) together with global warming potential (GWP) results. Similarly, CDDB is assumed to enter the plant without any prior environmental burdens and biogenic CO_2 emissions are hence excluded. This approach can be justified as CDDB gasified is not reducing carbon stocks e.g. in a forest or on agricultural land (the initial reduction in carbon stocks is fully allocated to the waste's previous life).

Conventional power generation. We use Ecoinvent data (23) to model the US average power mix (coal 47%, nuclear 20%, natural gas 17%, hydro 7%, others 9%) and electricity provided from hard-coal fired power plants. Electricity from the NE power grid is based on energy shares from NEPOOL (natural gas 42%, nuclear 30%, coal 12%, hydro 7%, renewables 6%, others 3%) (29), with respective US LCI (22) and Ecoinvent (23) entries being used to model environmental burdens of providing 1 kWh via the NE grid.

RESULTS AND DISCUSSION

Power plant performance. The net electricity generated per kg of feedstock is compared to literature data (SI: Table 2). Feedstock energy of woody biomass and coal used in this study is with 14 – 23 MJ/kg higher than typical energy contents of MSW. With the exception of route 6-Coal/Bio, electricity consumption (0.17 to 0.28 kWh/kg feed), syngas chemical energy (8 to 14 MJ/kg feed) and net electricity generated (0.51 to 0.90 kWh/kg feed) is fairly similar to data reported elsewhere (18,34,46). Differences for route 6 are due to high feedstock energy in combination with higher electrical conversion efficiencies (29%) of an anticipated commercial gasifier (using PGR simulation data). Electrical conversion efficiencies of pilot plants ranged between 13 – 20% (HHV), while for anticipated commercial plants this would be 25 – 29%. For regular solid waste gasification steam cycle plants the maximum net electrical efficiency is about 23% (15). However, modified turbine designs such as integrated gasification combined cycle (IGCC) allow net electrical efficiencies of up to 30 – 40% if thorough syngas cleanup is carried out prior to IGGC (15). This may be possible in a future design (see sensitivity analysis).

Life cycle impact assessment (LCIA). The LCIA was carried out using a combination of LCIA methods to evaluate midpoint impacts (Table 2) including global warming potential (GWP) (47), fossil depletion, land occupation, ozone depletion (ODP), water use (ReCiPe World (H/A) v1.05 (48)), and acidification, eutrophication, smog, and respiratory effects (TRACI v3.03 (49)). Single score endpoint impacts were assessed using the ReCiPe World (H/A) v1.05 method with more information available in the supporting information (SI: Figure 15). Information regarding life-cycle wide GWP may be of interest when determining the 'eligibility' of C&D wood for renewable energy credits in states of the NE U.S. (12). Impacts to smog and respiratory effects may inform waste- and decision-makers as well as the public regarding potential air emissions from novel conversion systems (6). Finally, land occupation estimates can provide valuable information in the context of limited land availability for bioenergy production (see introductory remarks). Detailed information on each impact category, a breakdown by life-cycle stage, and the sensitivity analysis can be found in the supporting information.

		-------------------CDDB and Forest Biomass-------------------				-------Coal and Forest Biomass/CDDB-------			--------Conventional Power Generation--------		
Impact category	**Unit per kWh**	**1-Bio**	**2-CDDB**	**5-Bio/CDDB**	**7-Bio/CDDB***	**3-Coal/Bio**	**4-Coal/CDDB**	**6-Coal/Bio***	**U.S. NE mix**	**U.S. average mix**	**Hard coal power plant**
GWP	kg CO2 eq	0.514	0.653	0.573	0.325	1.902	1.461	1.088	0.534	0.775	1.196
GWP (biogenic)	kg CO2 eq	1.93	2.32	1.58	1.08	0.96	0.70	0.46	0.00	0.01	0.00
Fossil depletion	kg oil eq	0.18	0.26	0.18	0.11	0.52	0.41	0.30	0.19	0.22	0.30
Land occupation	m2a	5.72	0.00	2.81	1.85	3.32	0.01	1.58	0.01	0.02	0.03
ODP	kg CFC-11 eq	2.00E-08	1.72E-08	1.86E-08	1.49E-08	2.29E-08	1.69E-08	1.60E-08	1.40E-08	2.03E-08	5.31E-09
Water use	m3	0.0032	0.0047	0.0039	0.0021	0.0042	0.0030	0.0017	0.0004	0.0021	0.0026
Acidification	H+ moles eq	0.123	0.190	0.118	0.069	0.142	0.109	0.065	0.213	0.275	0.393
Eutrophication	kg N eq	0.000344	-0.012725	-0.005332	-0.004218	0.000281	-0.004859	0.000146	0.000080	0.000143	0.000219
Smog	g NOx eq	0.00113	0.00129	0.00108	0.00067	0.00164	0.00116	0.00084	0.00081	0.00149	0.00257
Respiratory effects	kg PM2.5 eq	0.000486	0.000778	0.000371	0.000224	0.000467	0.000361	0.000225	0.001000	0.001450	0.002151

Table 2 LCIA results (per kWh) of plasma gasification routes utilizing various feedstocks and in comparison to conventional power generation.

*PGR based on computer simulation data.

Results indicate that with regards to GWP (0.325 – 0.653 kg CO_2-eq/kWh), fossil depletion (0.110 – 0.262 kg oil-eq/kWh), acidification (6.95E-02 – 1.90E-01 H+ moles-eq/kWh), eutrophication (-1.27E-02 – 3.44E-02 kg N-eq/kWh), smog (6.66E-04 – 1.29E-03 kg NO_x-eq/kWh), and respiratory effects (2.24E-04 – 7.78E-04 kg $PM_{2.5}$-eq/kWh), the use of CDDB and forest residues as gasification feedstock for electricity may result in environmental burdens slightly lower than electricity obtained from the NE or U.S. average power grid (Table 2). Impacts are mainly due to current system configurations in which coke is used as gasifier bed material, fuel oil is co-combusted in the boiler, and extensive syngas cleanup is applied (see supporting information). On-site emissions are minimal due to the nature of the plasma gasifier which removes a large fraction of inorganics present in the waste feedstock as vitrified slag and applies extensive syngas cleanup prior to combustion, therefore reducing gas volume to be cleaned.

Co-gasification with coal (routes 3, 4, and 6) significantly increases impacts, in particular to GWP (1.08 to 1.90 kg CO_2-eq) and fossil depletion (0.295 to 0.52 kg oil-eq), due to coal acquisition and fossil feedstock carbon emitted on-site during syngas combustion (Table 2). Coal inputs range between 0.28 kg (route 6) to 0.43 kg (route 3) per kWh electricity generated. This compares to roughly 0.47 kg of coal per kWh for traditional coal-fired power plants (23). In contrast to traditional combustion and gasification systems solely utilizing coal feedstock, the use of waste in a gasification-steam cycle boiler limits the overall plant electrical efficiency due to impurities present in the waste feedstock that have the potential to form acid gases (e.g. HCl, H_2S, etc.) at high temperatures potentially corroding tubes (15).

The avoided burdens of diverting CDDB from landfills are captured via system expansion and reduce overall impacts. This is particularly pronounced for eutrophication which is drastically reduced if CDDB is diverted from landfills, mainly as a result of avoided nutrient leaching.

It should be noted that with a GWP of 0.325 to 0.653 kg CO_2-eq per kWh (SI: Figure 2), biomass/CDDB gasification for electricity production results in much higher GHG emissions than data reported for other bio-power LCA studies. Heath et al (50) reported a GWP meta-analysis of various bio-power systems (co-firing, combustion, gasification) and found 25th and 75th percentile ranges of life-cycle GHG emissions of 0.015 to 0.065 kg CO_2-eq/kWh, respectively. Higher GWPs found in this study are primarily due to the current plasma gasification system configuration using fossil coke or anthracite as PGR bed material, oil co-combustion in the boiler to allow for a stable flame, and extensive cleanup using NaOH and other chemicals. This system configuration should not be seen as rigid since modified PGR systems may be able to operate with smaller amounts of coke, syngas cleanup may be further optimized in the future, and a different boiler design could allow the combustion of syngas without the need for fossil-based oil. In addition, electrical conversion efficiencies might be further improved using advanced turbine designs (see sensitivity analysis).

Land occupation (-6.84E-04 to 5.72E+00 m2a) is highest if forest residues are used as gasifier feedstock and lowest when CDDB is utilized (SI: Figure 6). This is due to upstream impacts associated with forest growth and harvest in the NE U.S. However, due to climatic conditions and natural regeneration assumed, land occupation results are region-specific for the NE U.S. Utilizing other biomass feedstock (e.g. short rotation crops on formerly degraded land) may be able to provide a suitable feedstock associated with lower land occupation. It should be noted that our analysis only accounted for land occupation, but excluded possible impacts as a results of changes in soil quality and land transformation. Such impacts should be included in a future study by extending the analysis to investigate related ecosystem pressures per m2 of land occupied, and by including land transformation (see e.g. (51).

Water use associated with gasification plants (1.70E-03 to 4.7E-03 m^3/kWh) is higher than for conventional fossil-based systems (4.2E-04 to 2.6E-3 m^3/kWh) due to extensive syngas cleanup (SI: Figure 8). This may be an obstacle for implementing those technologies in arid regions around the world.

Ozone depletion (ODP) (1.49E-08 – 2.28E-08 kg CFC-11-eq), associated with plasma gasification was found to be similar to NE and U.S. average power (1.41E-08 and 2.03E-08 kg CFC-11-eq) but higher than coal-fired power generation (0.53E-08 kg CFC-11-eq) (SI: Figure 7). ODP is mainly due to the unit processes of heavy fuel oil production for no. 6 oil provision co-combusted in the boiler, and sodium hydroxide provision for syngas cleaning.

Using computer simulation data for the PGR (routes 6 and 7) shows how, in a full-scale commercial facility, environmental burdens may be further reduced due to lower heat losses associated with feedstock gasification. In such a case, utilizing bio-based feedstock in the plasma gasification system (route 7) may have the potential to lead to environmental burdens lower than U.S. average power in all impact categories, except land occupation which due to forest residuals use is higher than for fossil-based power generation. Similarly, in a commercial plant coal used as co-gasification feedstock together with forest residuals (route 6) may allow energy provision that could compete with current coal-fired power plants in all impact categories excluding land occupation and ODP.

Sensitivity analysis. Environmental impact categories investigated were found to be sensitive to varying assumptions with regards to system expansion (avoided landfilling), slag/residue landfilling, and feedstock transportation distances (SI: Table 5). Excluding system expansion (avoided landfilling) from our model, leads to and increase in overall impacts, which is most pronounced for impacts to GWP (0.772 kg CO_2-eq), ODP (2.29E-8 kg CFC-11 eq), eutrophication (0.00053 kg N eq) and smog (0.001500 kg NOx eq). Similarly, including landfilling of gasifier slag/residuals in the LCA model and varying feedstock transportation distances by ±15% shows that the impact categories most affected include GWP, ODP, eutrophication and smog (SI Table 5). Varying assumptions with regards to coke/anthracite inputs, torch power, and turbine efficiencies are shown in (SI: Figure 17 and 18). Halving coke/anthracite inputs used as PGR bed material may result in a recognizable decrease in environmental burdens in particular with regards to fossil depletion potential (FD) (~30% reduction), respiratory effects and acidification (both ~20% reduction), as well as GWP and smog (both ~10% reduction). The lowest impacts are found if an increase in the turbine efficiency of up to 50% is assumed (this may be possible via IGCC, assuming thorough syngas cleanup prior to syngas being fed to the gas turbine). Assuming such a design, overall environmental impacts could be reduced by roughly 30% compared to current configurations. Using an economic allocation for the multi-output processes of ‘waste sorting’ and ‘wood growth/harvest’ would reduce upstream environmental burdens associated with these processes as low-value feedstock (i.e. forest residuals currently left in the forest to decay and C&D wood currently landfilled) are utilized (SI: Figure 18). As a result, impacts with regards to land occupation might be drastically reduced for all routes utilizing forest residuals and an economic allocation.

Outlook and recommendations. Using forest residues and CDDB as feedstock for plasma gasification allows the generation of a syngas suitable for electricity production. Using CDDB as gasifier feedstock would reduce the amount of waste landfilled, and decrease land occupation. However, with the exception of avoided landfilling (treated via system expansion) we do not discuss the possible consequences and indirect implications (e.g. changing demands for forest biomass, changes in CDDB recovered for recycling, etc.) of diverting large amounts of C&D wood or forest residuals to large-scale gasification systems in the NE U.S. This might be done in a follow-up study applying consequential LCA (Earles and Halog 2011; Ekvall 2000). In the current system configuration, life-cycle impacts of plasma gasification are largely influenced by the inputs of coke, anthracite (both gasifier bed material), and no. 6 oil (boiler), as well as water and chemicals inputs to the syngas cleanup system. In addition, low conversion efficiencies due to PGR heat losses and the use of a steam turbine, instead of more efficient gas turbine, limit the system-wide environmental performance. The gasification of other mixed waste feedstocks (e.g. MSW and industrial wastes) should be investigated in future studies. It should be noted that on-site emissions have been derived using a combination of existing data from our company partner and industry data from the literature on typical onsite emissions of MSW plasma gasification. These should therefore only be seen as a proxy of actual emissions which will vary depending on feedstock type, season, and syngas cleanup configuration. While plasma gasification seems to be competitive, in terms of environmental impacts, to fossil-based energy production, in order to compete with other bio-based energy systems (50) plasma gasification has to significantly reduce GHG emissions, particularly associated with fossil inputs and syngas combustion. Capturing carbon (CCS or CCR) from the gas stream prior to combustion offers advantages (52) and could help to reduce GWP-related impacts in future designs. However, the provision of a clean syngas also opens up future options of syngas utilization as feedstock for subsequent chemicals and fuels provision via various catalytic pathways (e.g. Fischer-Tropsch or Methanol-to-Olefins Synthesis) (53). Plasma gasification should therefore also be investigated in coupled systems using subsequent syngas catalytic conversion into chemical feedstock and in comparison to fossil-based fuels and chemical feedstock provision.

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SUPPORTING INFORMATION

This information is available free of charge via the Internet at http://pubs.acs.org.

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