Techno-Economic and Life Cycle Assessment of Lignocellulosic Biomass-Based Thermochemical Conversion Technologies: A Review

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Abstract

Bioenergy derived from biomass provides a promising energy alternative and can reduce the greenhouse gas (GHG) emissions generated from fossil fuels. Biomass-based thermochemical conversion technologies have been acknowledged as apt options to convert bioresources into bioenergy; this bioenergy includes electricity, heat, and fuels/chemicals in solid, liquid, and gaseous phases. In this review, the techno-economic and life cycle assessment of these technologies (combustion, gasification, pyrolysis, liquefaction, carbonization, and co-firing) are summarized. Specific indicators (production costs in a techno-economic analysis, functional units and environmental impacts in a life cycle analysis) for different technologies were compared. Finally, gaps in research and future trends in

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biomass thermochemical conversion were identified. This review could be used to guide future research related to economic and environmental benefits of bioenergy.

1. Introduction

Fossil fuel depletion and adverse environmental impacts are two major concerns of rapid industrialization and technology development. As fossil fuel is an easily accessible and available source of energy, most of the world's energy consumption is fulfilled from it. However, this energy production and use is associated with high greenhouse gas (GHG) emissions and particulate matters. It is necessary to address these problems.

Renewable sources of energy could be an alternative that can replace fossil fuels. Among all the renewable sources, biomass is the only resource that can be directly converted to high value end products (bioenergy and biofuel) in any form (solid, liquid, or gas) using thermochemical conversion technology [1]. These technologies rely on lignocellulosic biomass feedstock (e.g., agricultural residue, forest residue,) to form various fuels and chemicals [2]. Lignocellulosic biomass feedstocks do not compete with food sources are getting a lot of attention. However energy crops which are specifically grown for energy production might compete with conventional crops for land use especially when farmers receive subsides for cultivating energy crops [3]. In some cases there is a potential of growing the energy crops on the marginal land [4, 5] and this case these would not compete with conventional crops for land.

The thermochemical conversion of biomass to useful end products can occur through one over several: pyrolysis, gasification, liquefaction, combustion, carbonization, and co-firing. Pyrolysis is considered to be the starting point of all thermochemical conversion technologies because it involves all chemical reactions to form solid, liquid, and gas as the main products with zero concentration of oxygen. Thermochemical conversion focuses on both gaseous or liquid intermediates and their upgrading into more valuable forms of energy (transportation fuels, chemicals, electricity, etc.)

There are few review papers that directly address both techno-economic assessments (TEA) and life cycle assessment (LCA) analyses of thermochemical conversion of lignocellulosic of biomass. However, a few authors have reviewed these issues individually for a few of the technologies. A comparative technical and economical assessment of biomass pyrolysis, gasification and combustion for electricity generation has been done by Bridgwater et al [6]. They concluded that combining diesel engine with fast pyrolysis technology has great potential to generate electricity, for the long term and for profit. A TEA analysis of lignocellulosic ethanol has recently been done by Gransounou and Dauriat [7]. Damartzis and Zabaniotou have discussed the production of second generation biofuels from biomass using thermochemical conversion and identified challenges and opportunities in the application of process integration [8]. Muench and Guenther have done a quantitative LCA analysis of biomass conversion to heat and electricity through thermochemical and biochemical pathways [9]. Finally, Menten et al. wrote a review paper on GHG emissions for advanced biofuels using meta regression analysis for thermochemical conversion of lignocellulosic biomass [10]. The above-mentioned papers are the few review papers that partially addresses the issues.

This review paper focuses on LCAs and TEAs of various routes of thermochemical conversion technology. An LCA analysis is a useful tool to identify potential environmental impacts of end products from the various processes in the whole life cycle. It is a system to evaluate the material and energy inputs and outputs in terms of end products and emissions as well as different environmental impacts of the products during their life cycle. Generally, the International Organization for Standards (ISO) 14040 series has been used for an LCA analysis, but the calculation is not that straightforward as this analysis is a data-intensive method. With the ISO 14040 series, an LCA analysis will have four basic steps: a goal, scope and boundary definition; life cycle inventory analysis; life cycle impact assessment; and interpretation of the result [11]. Feedstocks, functional units, system boundaries, and environmental effects are identified as the influential aspects of an LCA analysis.

The economic features of these thermochemical conversion routes can be reflected through a TEA, where the production cost of each product is summarized and compared for different conversion routes. This paper reviews the literature on TEA and LCA on the conversion of lignocellulosic biomass to useful end products through thermochemical conversion. In addition this paper identifies gaps in research in this area. The conclusions of this review paper can assist in addressing the knowledge gap in this area.

2. Biomass thermochemical conversion pathways

2.1 Available technologies

The thermochemical conversion of biomass to produce useful end products from the initial feedstock can occur through one of six different conversion pathways: pyrolysis, gasification, combustion, co-firing, liquefaction, and carbonization. Table 1 summarizes the different types of thermochemical conversion processes, their classification, process conditions, reactors used, and the product yield.

Pyrolysis: Pyrolysis involves the production of three different phases of products with various chemical reactions of feedstock in the absence of air. Depending on the process condition, pyrolysis is further divided into six subcategories, which are shown in Table 1. Fast pyrolysis is widely used to enhance the liquid yield with moderate temperature and very low residence time. Charcoal is the main product of slow pyrolysis at a low heating rate, longer vapor residence time, and moderate temperature. Particle size distribution plays an important role in pyrolysis as lignocellulosic biomass is a nonconductor by nature [12].

Gasification: Gasification is another kind of thermochemical conversion process that generates gaseous precursors in the presence of a gasifying agent such as steam, air, oxygen, etc. Gasification is also known as the extension of pyrolysis that is optimized to enhance the gaseous yield compared to liquid and solid phases. The use of oxygen in place of air as a gasifying agent, which eliminates nitrogen as a diluent, produces high calorific value gases as the final product. The heating rate, reactor design, and post-processing of gases are the main controlling factors for producing clean, high quality gaseous products from gasification [13].

Co-firing: Biomass co-firing with coal is a low-cost technology for efficiently and cleanly converting lignocellulosic biomass to electricity [14]. In this process, the primary fuel (coal) is partially substituted by biomass in a high efficiency boiler. Depending on the boiler capacity and efficiency, the percentage of biomass co-firing varies between 5 and 20 by weight [15]. The substitution of

biomass has a positive effect environmentally. Co-firing takes the advantage of the power plant's economies of scale and saves fossil fuels.

Liquefaction: This process is also known as hydrothermal liquefaction as water plays an important role in this thermochemical conversion. Water at high temperatures behaves as a reactant and as a catalyst that causes organic material to disintegrate and reform by adding hydrogen ions into the hydrocarbons. The main advantage of liquefaction over pyrolysis and gasification is that liquefaction does not require dried biomass as the initial feedstock (drying is an energy-consuming process) [16] and it reduces the number of unit operations required in the conversion of biomass to liquid fuels. This process is the direct conversion of biomass to liquid fuels.

Carbonization: Carbonization is also an extension of the pyrolysis process at a slow heating rate where a carbon-rich solid residue is the dominant product with less liquid and gas yield. The formation of solid bio char depends on the operating temperature of the process [17].

Combustion: Biomass combustion is the simplest thermochemical conversion technology that takes place in presence of air. Heat, power, or combined heat and power are the main products of direct combustion of lignocellulosic biomass. This process consists of consecutive heterogeneous and homogeneous reactions. Biomass combustion basically depends on the particle size and properties of the feedstock, temperature, and combustion atmosphere. High emissions of NO_x, CO_2, and particulate matter, as well as ash handling make this process highly challenging from an environmental point of view [18].

Table 1.

2.2 End products

Figure 1 shows the primary products (solid, liquid, and gas) and end products from the six main thermochemical conversion technologies. The bio-oil produced from pyrolysis can be directly used in place of fuel oil or diesel in static operations such as a boiler, turbine, or engine to generate electricity. It can also be upgraded to a transportation fuel through hydroprocessing in the presence of hydrogen and a catalyst [34]. A wide range of chemicals such as resin, fertilizers, etc., can be extracted from the bio-oil. The product gas can directly be used in a boiler, gas turbine, engine, or fuel cell to produce electricity, heat, or combined heat and power. A range of chemicals can also be derived from this gas. High heating value gas, produced from gasification by using oxygen as a gasifying agent, can be converted to a transportation fuel [30]. Solid char is the main output of the carbonization and slow pyrolysis process. The solid residue known as biochar can be used as soil conditioner, insulation, or a catalyst (as activated carbon) and can reduce global warming emissions.

Figure 1.

3. Techno-economic assessment (TEA)

Biomass use has got received more attention in recent years due to its environmental benefits. However, widespread implementation of biomass mainly depends on the cost competitiveness of biomass-based fuels and chemicals compared to those produced from

conventional fossil sources. A TEA of biomass thermochemical conversion technologies is important for its development and commercialization, and one of the key outcomes of a TEA is the cost of producing fuels and chemicals. Production cost can be estimated by developing discounted cash flow sheet models for a biorefinery. The production costs are specific to thermochemical conversion technologies and the products.

The techno-economic performances of mainly thermochemical technologies such as combustion, gasification, and fast pyrolysis for power generation were assessed by Bridgwater et al. [6]. Equations for the capital cost and operating cost for each of these technologies were derived by Bridgwater et al. Those equations provide useful information for an economic assessment of one specific process. The products from biomass thermochemical conversion include electricity, bio-fuels, and bio-chemicals. Economic analyses of these products were done by deriving the production cost of each product. Tables 2-3 summarize the production costs of different products (bio-chemicals/bio-fuels and electricity) from different biomass thermochemical conversion technologies. All the cost data mentioned in this review are in 2014 US$ and an inflation of 2% is used. The production costs will be discussed and compared for each technology later in this paper. Figure 2 and 3 represents table 2 and 3 respectively to give a brief idea of cost comparison of different biofuels to the readers.

Table 2.

Table 3.

Figure 2.

Figure 3.

3.1 Gasification

Biomass can be gasified into syngas, which can be further converted into bio-fuels and bio-chemicals and can also be used in a gas turbine for power generation. Fischer and Pigneri evaluated the economics of power generation from biomass gasification in Vanuatu and concluded that a small-scale biomass gasifier with a readily available feedstock supply could be more economical than generating power from a similarly sized diesel generator [54].

A gasifier can be operated under high pressure or atmospheric pressure. Table 2 lists the production costs of some bio-chemicals (methanol, ethanol, dimethyl ether, Fischer-Tropsch fuel, and ammonia) that can be produced from either a pressurized or atmospheric pressure gasifier. As shown in Table 2, the production costs of chemicals/fuels from a pressurized gasifier based plant are higher than those from an atmospheric gasifier based plant [35]. For example, the production costs of methanol from atmospheric and pressurized gasifiers are $0.29/kg and $0.45/kg, respectively, under the same capacity at 2000 dry tonnes/day. A similarly trend can be found for the production cost of dimethyl ether, ammonia, and Fischer-Tropsch (F-T) fuel. This is mainly because the capital costs of pressurized equipment are much higher than those of atmospheric equipment. The cost of a pressurized gasification system can be four times the cost of an atmospheric system for a power plant with a capacity of 20 MWe [55]. Another reason for the high production cost of a pressurized system is the high cost of the feeding process due to the complex feeding section of the system. However, despite the higher cost of the pressurized gasifier, it is more efficient than the atmospheric system, especially at high capacities.

Most feedstocks for gasification are woody biomass, agricultural biomass, and some energy crops. The economics of biomass gasification depend on the biomass feedstock. For example, for hydrogen production, woody biomass, such as forest residues or whole trees, has a lower production cost (around $1.17-1.3/kg) than agricultural biomass (around $1.29-1.33/kg), as shown in Table 2.

Co-gasification of biomass with coal provides a feasible option because the high volatile matter content of biomass can help for auto-thermal gasification [56]. Cormos evaluated the co-gasification of biomass and solid wastes with coal for poly-generation based on an integrated gasification combined cycle (IGCC) with carbon capture [57]. The products generated include power, hydrogen, synthetic natural gas (SNG), and liquid fuel. The conclusion showed the advantages of the poly-generation of power with other chemicals and fuels. For example, the plant payback period decreases with increased hydrogen co-production with power. The payback period also decreases with increased co-generation of SNG and F-T fuel with power.

3.2 Combustion

Several boiler types can be used for biomass combustion for power generation. Generally, pulverized coal-fired (PC) boiler with biomass feedstock co-fired with coal gives a lower cost of electricity (COE) than do fluidized bed boilers, as shown in Table 3. When compared with different fluidized bed boilers, circulating fluidized bed (CFB) boiler normally generate electricity at a lower cost than does a bubbling circulating bed (BFB) boiler. Moreover, a supercritical boiler (PC or CFB) has lower COE than a subcritical boiler. A solely biomass-fueled power plant normally has a higher COE than a coal power plant when the biomass price is higher than coal, and this high COE can be reduced by co-firing biomass with coal (see Table 3).

A conventional biomass power generation system normally has a high break-even electricity selling price (see Table 3) when compared with a co-generation plant, due mainly to the high installation cost. The co-generation of heat with power provides a more economical solution. A biomass combined heat and power (CHP) configuration analysis shows that the high electricity production cost can be compensated by heat production [50]. The capital cost of an Organic Rankine Cycle (ORC) based CHP plant has A higher initial capital investment than a gasification-based CHP plant. However, the ORC-based CHP unit offers economic benefits such as a lower break-even electricity selling price than the gasification-based CHP unit. The main reason for the lower price is the large amount of heat generated from the ORC-based CHP unit, which improves the economic performance significantly [50].

3.3 Pyrolysis

There are several types of bio-products from biomass fast pyrolysis. The main and direct product is bio-oil, which can be further upgraded into transportation fuels or bio-chemicals. Additionally, fast pyrolysis can be used to generate power with a combination of diesel engines.

Bio-oil production costs from the fast pyrolysis of energy crops (such as miscanthus and willow) have been estimated to be $12-26/GJ [41] with variable feedstocks and plant sizes. Two important factors that impact the production costs of bio-oil from a pyrolysis plant are electricity consumption and surplus char selling. Electricity is primarily consumed for biomass handling and processing. It was estimated that if part of the bio-oil were used in a diesel engine for power generation to provide the internal electricity for the

pyrolysis plant, around 18% of the produced bio-oil would be consumed. Selling the pyrolysis by-product char can help to reduce the production cost by up to 18%, though the selling price depends on the market for char.

Transportation fuels that can be produced from biomass fast pyrolysis and hydroprocessing have been studied extensively. This pathway includes the initial production of bio-oil from biomass by fast pyrolysis, followed by the upgrading of the bio-oil into a transportation fuel by adding hydrogen. Wright et al. investigated naphtha and diesel produced from bio-oil and concluded that the production costs of transportation fuels would be $0.56-0.82 per liter (base year of 2007) with a capacity of 2000 dry tonnes per day (see Table 2) [49]. The variation in the production costs depends on the source of the hydrogen. When hydrogen is produced from the process itself, transportation fuel production costs, are higher than when hydrogen is purchased from outside of the system. The main reasons are the fuel conversion yield and biomass price, both of which have a significant impact on the production cost. The production cost of transportation fuels (gasoline and diesel) derived from fast pyrolysis followed by hydroprocessing were estimated by by Brown et al. [47] to be $0.68 per liter (base year 2011) with a capacity of 2000 dry tonnes per day (see Table 2) This is the same range suggested by Wright et al [49].

The fast pyrolysis and diesel engine system provides a feasible option for power generation. The electricity production costs of a fast pyrolysis and diesel engine system range from around $0.14/kWh (base year 2002) at 1 MWe to around $0.07/kWh (base year 2002) at 20 MWe. This is higher than in an established combustion system, and lower than any other novel biomass power generation system such as integrated gasification combined cycle (IGCC) or a gasification combined engine system [6]. However, the fast

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pyrolysis and diesel system is inefficient and not suitable for t high capacities. The two main reasons for the low efficiency are the low energy conversion rate of feedstock into pyrolysis liquid, which affects yield and hence electricity production costs, and the high power consumption for feedstock grinding.

There are several potential solutions to improve the economic competitiveness of power generated from biomass fast pyrolysis and diesel engine systems: waste disposal, water, heat and by-product char selling, or co-generation of bio-chemicals with power [6]. Systems decoupling is another option that helps the fast pyrolysis and diesel engine system to be more competitive for power generation. Decoupling means that several decoupled diesel engines are served by a large, fast pyrolysis plant. The electricity production cost of a decoupled system is much lower than the traditional close-coupled systems [6] due to the benefit of economy of scale in the pyrolysis plant. In addition, a decoupling system can better meet the power load requirements at peak and off-peak times because the pyrolysis plant and generator operate independently.

Bio-char and methanol can be co-generated from the slow pyrolysis process of biomass [37]. The char production cost from this process depends on the pyrolysis temperature; a lower temperature reduces production costs. Furthermore, the production costs of bio-char significantly affect the co-generation plant's profits, especially at lower temperatures because of higher char yield. For example, in the case from a study by Shabangu et al. [37], 70% of the plant revenue is from selling bio-char and 30% is from methanol when the pyrolysis temperature is 300 °C. When the temperature increases to 450 °C, 30% of the revenue is from char and 70% from methanol.

Another process for co-generation of bio-char and methanol is gasification. Different with slow pyrolysis process, the impact of char price on the revenue is not important in gasification process because there is the char yield lower compared to that of slow pyrolysis.

3.4 Liquefaction

Biomass can be converted into liquid fuels in three ways: fast pyrolysis followed by hydroprocessing, gasification with the Fischer-Tropsch synthesis and hydroprocessing, and biochemical conversion. The production costs of these liquid fuels range from $0.53-$1.45 per liter gasoline equivalent in 2007 US$ with a capacity of 2000 dry tonnes per day, based on an assumed feedstock price of $82.7 per dry tonne [58]. Different pathways affect the production costs more significantly than the factors within a specific pathway (i.e., the temperature, oxygen feed flow rate, and gasifier type in the gasification system). The maturity and implementation of each pathway's technology also affect the production costs significantly.

Because of lower total capital investment, direct liquefaction through fast pyrolysis has a lower production cost (around $0.56-0.975/L as shown in Table 2) than does liquefaction though the gasification or biochemical pathway. Specifically, direct liquefaction by fast pyrolysis followed by upgrading bio-oil into liquid fuel by adding merchant hydrogen shows an even lower production cost when compared with producing hydrogen from pyrolysis itself. However, the process of producing transportation fuel from upgrading bio-oil from pyrolysis is not fully defined; that is, it is relatively immature and is not in wide use, and thus further development is required before this technology can be implemented on a large scale.

Liquid fuels produced from gasification with further upgrading usually have higher production costs (around $0.53-$1.64/L; see Table 2.) than fuels produced from pyrolysis. Trippe et al. [44] studied the breakdown of the specific production costs of gasoline and diesel from biomass gasification followed by a Fischer-Tropsch synthesis and found that syngas feed costs make up the largest part to the production cost. The syngas feed costs mainly include the operating cost of biomass gasification, syngas cleaning and conditioning. The capital costs of the liquefaction through gasification pathways are higher than those through pyrolysis and biochemical pathways at both high and low temperature scenarios. However, the production costs of liquid fuel from the gasification pathway are lower than those of fuel from biochemical conversion, which mainly benefits from the low operating cost. When comparing different gasification technologies in terms of transportation fuel production cost, Swanson et al. [48] evaluated two gasification scenarios with the same syngas synthesis process. The first scenario is at a low temperature with a fluidized bed, and the second scenario is at high temperature with an entrained flow gasifier. The high temperature technology has a lower production cost than that of the low temperature one, mainly because of the high product yield, even though the capital cost is also high for the high temperature scenario. The liquefaction of biomass through a gasification pathway is yet to be commercialized. It is worth mentioning that the production costs of a pioneer plant are 60-90% higher than those of an nth plant and capital costs will be more than double those of an nth plant [48].

Except for bio-oil, another intermediate for biomass-to-liquid fuel production that is under research is biosyncrude. Different compared to conventional bio-oil, biosyncrude is a mixture of pyrolysis liquids and char, which are produced from biomass fast pyrolysis. The production of biosyncrude is being investigated in Germany [39], and can be produced at a cost of $14.4/GJ, (base year

2008) with a capacity of 600 tonnes/day. This cost is higher than that of natural gas ($9.06/GJ) and coal ($6.18/GJ) in Germany. 50% of the cost is biomass feedstock cost and 30% is investment-dependent. Personnel and electricity consumption costs are insignificant.

3.5 Co-firing

Biomass co-firing with coal/natural gas could be a competitive thermochemical conversion technology due to its environmental benefits when compared with only coal combustion [14]. The fluidized bed technologies have been found to be good options for co-firing coal with biomass/plastic waste because of their "fuel flexible" feature. The effect of blending up to 20% of biomass/plastic waste in a circulating fluidized bed (CFB) is negligible for the performance of the co-firing system when compared with systems fuelled solely by coal [56].

When assessing the economic analysis of a biomass co-firing plant with an existing coal-fired plant, the total additional cost including capital and operating costs from blending biomass can indicate the economic attractiveness. De and Assadi studied the economics of biomass co-firing with several operating parameters such as plant capacity, biomass substitute ratio, feedstock price, and biomass distribution density around the plant [59]. It was concluded that when biomass costs more than coal, increasing the co-firing rate leads to an increase in co-firing cost and hence an increase in cost per unit of electricity. The specific additional cost per unit of electricity slightly decreases with a higher distribution density of biomass around the plant and the remaining life of the plant.

Biomass co-firing can be combined with gasification for economic efficiency in a process in which biomass-derived gas is indirectly co-fired with natural gas. Rodrigues et al.[53] calculated the electricity production costs to be $59/MWh in the base year 2003 for 150

MW of biomass power in a 50% natural gas co-fired plant . As a comparison, the production cost for a 24 MW biomass-fired system is $94/MWh.

3.6 Comparison of the economics of different technologies

The economics of biomass conversion pathways significantly depend on the end products. For example, hydrogen can be produced from both gasification and pyrolysis followed by steam reforming (see Table 2). The production cost of hydrogen from pyrolysis and steam reforming is almost double the cost of gasified hydrogen. However, for transportation fuels like gasoline or diesel, the production cost from gasification is higher than that from pyrolysis. For power generation from pyrolysis and gasification, power generation from pyrolysis with a diesel engine system has a lower capital cost and a lower electricity production cost than the gasification system; however, fast pyrolysis with a diesel engine is an inefficient means of generating power.

Bio-oil gasification and bio-oil reforming for hydrogen production have been compared by various researchers. It was shown that the bio-oil reforming process is more economical than the bio-oil gasification process [60]. The higher capital cost of bio-oil gasification (compared with the reforming pathway) is from the highcost of entrained flow gasifiers compared with the lower costs of reformers and air separation as well as a more complicated syngas cleaning process in the gasification system than the reforming system [60].

A TEA of electricity generation using CFB by both combustion and gasification was done by McIlveen-Wright [56]. Most of the techno-economic indicators were calculated. A CFB gasification system is more efficient (at 46.5%) than a CFB combustion system (40.5%). The CFB gasification has a lower specific investment and cost of electricity production than the combustion system. The

specific investment is $2150-2400/kWe for a CFB combustion system and $1350-1450/kWe for the CFB gasification system. The electricity cost is $68-78/MWh for the combustion system and $49-54/MWh for the gasification system [56].

A form of technology that is gasification combined with fermentation has been compared with conventional enzymatic hydrolysis-combined fermentation technology for ethanol production [61]. The gasification and fermentation process has a much higher ethanol production cost than the ethanol from the enzymatic hydrolysis and fermentation process. The main factors for this higher cost are high capital cost, high energy recovery expense, and relatively moderate ethanol yield. However, there are still potential advantages for the wide application of ethanol production through gasification and fermentation. One is the gasification process's co-generation of electricity with ethanol, which will recover the high production cost considerably. Another is that gasification is a much more flexible technology than hydrolysis [61].

4. Life cycle assessment analysis

Biomass-derived end products have emerged as a means to mitigate GHG emissions from different energy demand sectors (such as the transportation sector, the industrial sector, etc.) A life cycle assessment (LCA) is a useful tool to demonstrate different impact categories quantitatively and qualitatively involved throughout the life cycle of the end product.

The generalized system boundary for the thermochemical conversion of lignocellulosic biomass to useful end products includes three major phases: 1) biomass planting, harvesting, and transportation, 2) plant site operation and upgrading of primary products if

required, and 3) demolition and recycling of the plant (see Figure 4). Given the availability of data, phases 1 and 2 have been thoroughly studied by different researchers. The available literature on the LCAs is on pyrolysis, gasification, co-firing, and the combustion process. There is a lack of research on the LCA of carbonization and liquefaction and hence there is a need for comprehensive assessments on these. Different softwares (GREET [Greenhouse gases, Regulated Emissions, and Energy use in Transportation], SigmaPro, GHGenius, TEAM [Tools for Environmental Analysis and Management] etc.) are used by different authors for the inventory data collection for the analysis [62-64]. Eco Indicator 95/99 and CML (developed by Institute of Environmental Science of Leiden University) are used to calculate the environmental impacts of different feedstocks based on the system boundary considered for the process [65, 66].

Figure 4.

The following section of the paper is a review of the literature on lignocellulosic biomass LCA analyses. These papers basically concentrate on the thermochemical conversion technologies used to produce different end products from lignocellulosic biomass feedstock. Of all the technologies, pyrolysis is identified by different authors as the most widely studied process. Feedstock, system boundary, functional unit, and environmental impact are the parameters that have the greatest influence on an LCA.

4.1 Feedstock

Lignocellulosic feedstock type is an important consideration in thermochemical conversion technologies. Lignocellulosic biomass primarily consists of cellulose, hemicellulose, and lignin, but the concentration of these components varies with the type of feedstock.

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A higher percentage of cellulose and lower fraction of lignin are desirable for the process. For this review paper, we have focused on three types of lignocellulosic biomass feedstocks: energy crops, forest residues and agricultural residues (see Table 4). A particular type of feedstock has specific environmental impacts depending on its cultivation and the collection method.

Energy crops are known as third generation biomass; they were developed in order to produce a useful, low-maintenance energy supply source. These crops are also known as high yield or short rotation crops and their properties are genetically modified to get high energy yields in order to compete with fossil fuels [67]. The main disadvantage of these types of crops is the associated use of herbicides and pesticides, which could result in resistant weeds and insects that may be dangerous for non-genetically modified agricultural crops [68].

Forest residues are generated from post-harvesting timber extraction operations from forests, from leftover wood waste from lumber mills, or waste from rough or rotten dead wood. Forest residues are almost identical to wood in terms of heating value and moisture content but could have different ash content. In addition, the moisture content of the residues changes in the forest [69].

The third type of biomass feedstock is agricultural residues, which consist of unused portions (straw or husk) of frequently harvested agricultural crops such as wheat, corn, rice, etc. Corn stover, rice husk, and wheat straw are frequently available agricultural residues worldwide and have a low moisture content and high heating value. Crop seasonality and competing use of these residues (food for animals, soil improvement) increase the demand for this feedstock. Commonly a certain portion of these residues is used to improve

the soil conditions and ground water levels by protecting the soil from direct sunlight, rain, and wind [70]. Therefore in an LCA it is important to assess the impacts of the use of feedstocks for production of fuels/chemicals.

Table 4.

4.2 Different phases involved in a system boundary framework

The generic LCA framework for the thermochemical conversion of lignocellulosic biomass to different end products has three phases. Figure 4 shows both the phases and the required inputs and outputs from the different phases. Most researchers have used only phases 1 and 2 in the system boundary for their LCA (see Table 4). But a few have done the complete analysis from cradle to grave by including all three phases in the system boundary.

The first phase includes two main steps, the cultivation/collection of biomass (bale/chip formation, storage) and the transportation of biomass to the plant site.. Important aspects of this phase are land use change, carbon sequestration, application of fertilizers and pesticides, the effect of the removal of biomass residue from soil, and transportation distance from the biomass storage site to the plant site. Land use change has direct and indirect effects on the environment. Direct land use change is through the conversion of forest land or grassland to cropland for the production of biofuels/power. Indirect land use change occurs when non-cropland is converted to cropland for food production because existing croplands are used for biofuels production [84]. Most of the studies do not account for

land use change in the LCA analysis; this change directly ignores the change in carbon contained in the converted land for feedstock. Kimming et al. have suggested that set-aside lands (lands not used for food production due to legislative or practical reasons) that are not harvested be used for energy crops to maintain the carbon stock in the soil [79].

Energy crops have higher GHG footprint than conventional crops due to the application of chemical fertilizers and pesticides. According to Skowronska and Filipek, energy consumption for the production of 1 kg of NPK (nitrogen, phosphorus, and potassium) fertilizer is 9.91 MJ, and a significant portion of this energy is used for nitrogen production [85]. The infrastructure and production technology for a fertilizer facility put an extra burden on the environment as such a facility is a significant source of nitrogen oxide, methane, and carbon dioxide emissions [85]. To address the issue of food scarcity, the production of agricultural crops is increasing with the support of agrochemical inputs with limited land assigned for this purpose. But soil quality and sequestered carbon deteriorate with the frequent application of chemicals (which cause the leaching of nitrates). Therefore, the same authors have suggested replacing the mineral fertilizers with organic ones or with waste from biomass fermentation from a biogas plant [85].

The removal of agricultural residues from the soil could have an adverse effect on the environment if, for instance, appropriate amounts of straw are not left in the field.. The inappropriate removal of straw from croplands could reduce soil organic matter and nutrients from the soil and could also reduce the yield of biomass over time. Inappropriate removal of straw from agricultural lands could also have a negative effect on the ability of ammonia to volatilize due to the reduction in the immobilization of mineral fertilizer

[86]. Therefore, straw management is important because of the use of straw in the production of fuels and chemicals and needs to be included in an LCA [86].

The transportation of biomass from the plantation site to the facility is also an important aspect of the system boundary. Generally, it is assumed that the facility is near the plantation site; the proximity reduces the environmental impacts of transportation. A range of transportation distances of 30 to 200 km was considered in the literature reviewed for this paper. The distance depends greatly on the size of the biomass facilities and is necessary to determine the overall life cycle of the GHG emissions of a conversion pathway.

Phase 2 of the system boundary consists of biomass pretreatment (biomass crushing, grinding, and drying), biomass conversion technologies, and upgrading intermediate products if required. Biomass pretreatment conditions vary from process to process. Particle size distribution and moisture content after drying depend on the requirement of the conversion processes. Therefore different conversion technologies are also reasons for the variation in overall environmental impact categories. Based on the available data, four thermochemical conversion technologies (pyrolysis, co-firing, gasification, and combustion) were considered. The construction material for the equipment used in the facility depends on process conditions such as temperature, pressure, heating rate, etc. For example, to store the bio-oil (a highly viscous, polar, and corrosive liquid) a stainless steel storage vessel is needed. However, fossil fuels are required to extract iron ore and manufacture stainless steel from that ore, making the storage vessel a high source of GHG emissions [87]. Therefore reduction of GHG emissions is a key challenge for this phase.

Phase 3 of the LCA system boundary is the recycling and demolition of the facility at the end of its lifetime. This phase involves: 1) demolition of the plant, 2) the extraction, transportation, and recycling of the metals used in the plant's equipment, and 3) transporting of unrecyclable material to a landfill. This phase is one of the gaps in the current LCA literature.

4.3 The functional unit

The functional unit is a critical part of an LCA and needs a clear definition. It is a measure of the function of the end product rather than the physical product itself. The functional unit should be measurable and in line with the defined objectives of the study, which connect the social benefits to the environmental impacts. The choice of a functional unit is very important because it serves as the reference point against which all environmental impacts are evaluated. But selecting the functional unit is not straightforward, and differences in functional units can create problems in a life cycle inventory. Different authors choose different functional units depending on their goals and scope definition (see Table 4). Typical functional units chosen by authors are calorific value of end products, mass of the feedstock, transportation distance covered, and area of land used for feedstock cultivation (see Table 4). In addition, authors have selected different functional units based on their system boundary. For example, a functional unit of 1 MJ or 1 kWh or 1 MWh is apt for comparing energy-based end products such as heat, electricity, gasoline, and diesel. The functional units of area and distance, however, are not used frequently by authors. Comparing the different functional units is a challenging task, but it can be done if all functional units are converted to same unit, provided that boundary conditions are same for all the LCA studies [88].

4.4 Environmental impact assessment

An environmental impact assessment is the most crucial step that is performed after defining the system boundary and the inventory requirement for the product or process. Eco indicator 99 and Eco indicator 95 are generally used to calculate the different impact categories such as human health, ecosystem, and resource depletion. These impact categories are further divided into different environmental effect types. The ecosystem is subdivided into global warming potential, ozone layer depletion, acidification and eutrophication; human health into smog and toxics substances (heavy metals, carcinogens and pesticides); and resource depletion into solid waste and energy consumption. Table 4 summarizes the environmental effects considered by different authors. Global warming potential is the most common studied sub impact category in an ecosystem followed by acidification and eutrophication. Human health and resource depletion have been given less attention than the ecosystem. Global warming potential is reported in terms of CO_2 equivalent, which counts CH_4, N_2O, and CO_2 emissions in particular. Similarly, acidification and eutrophication are estimated in kg SO_2 equivalent and kg PO_2 equivalent, respectively.

Sebastián et al. stated that fertilizer production and application have greater GHG emissions than a biomass plantation. During biomass cultivation, the net release of CO_2 is negligible due to photosynthesis [15]. According to Sebastián et al., agricultural residues perform better environmentally than do energy crops, though energy crops are low maintenance [15].

Pretreatment of biomass is an energy-intensive step depending on the requirement of the thermochemical conversion method. Biomass pretreatment includes crushing, grinding, pellet making, and drying. The energy input for this process is directly proportional to the moisture content and inversely to the particle size reduction for the feedstock. Generally, the moisture content of agricultural residue

(10 -20 wt%) is comparatively lower than that of forest residues and the whole forest (40 -50 wt%) [69]. Therefore energy consumption varies with the moisture content of the feedstock. Iribarren et al. concluded that pretreatment of poplar had the greatest environmental impact compare to other unit operation in fast pyrolysis process because of the direct utilization of fossil fuels [19].

Particle size distribution of lignocellulosic biomass varies with the process requirement. Biofuel yield in a pyrolysis process generally decreases and char yield increases with an increase in particle size distribution, which is undesirable [19]. Energy consumption to reduce the particle size of biomass feedstock from 25 mm to 3 mm is 443 MJ/dry tonne of biomass compared to the 157.5 MJ/dry tonne required to decrease the particle size from 300 mm to 25 mm [89].

Environmental impact assessments vary with the operating conditions (temperature, pressure, reactor type, and heating rate of different thermochemical conversion technologies). Plant construction and material used for equipment are associated with GHG emissions. An increase in the percentage of biomass co-firing reduces the environmental impact but also reduces the efficiency of the boiler in electricity production [15].

Rafaschieri et al. examined the different gasification conditions for polar energy crops in a pressurized fluid bed gasifier and stated that the use of air as an oxidizer in place of oxygen reduces the environmental effects. The reason behind this is the oxygen produced from air separation consumes large amounts of electricity, which in turn produces GHG emissions [78].

5. Conclusion

Though techno-economic analyses on different biomass thermochemical technologies have been carried out recently, most of them focus on calculating the cost of one specific production chain for one product; there is no integrated techno-economic investigation of multiple routes of product co-generation. This gap needs to be addressed in future techno-economic assessment studies on biomass thermochemical conversion process.

Likewise, economic assessments on pyrolysis technology for liquid fuel production have been investigated extensively, but there should be more research on assessments focusing on upgrading pyrolysis oil into high-level liquid fuels and chemicals. The co-generation of these fuels and chemicals from pyrolysis seems to be the focus of future research and development as it might have both economic and environmental benefits. In terms of power generation from biomass, more techno-economic investigations are needed on novel power generation systems such as the fast pyrolysis and diesel engine system, the gasification with gas turbine or engine system, and the IGCC system. Of the techno-economic assessment of biomass liquefaction, although extensive work has been done on three platforms (gasification, pyrolysis, and bio-chemicals), more research is required on economic assessments of the co-generation of bio-fuels and bio-chemicals through these processes. For biomass co-firing, more techno-economic work should be done to increase the biomass substitution ratio and plant capacity. Very little research has been done on techno-economic assessments of biomass carbonization.

In the past few decades, there have been several LCA studies on the thermochemical conversion of lignocellulosic biomass, and these were reviewed in this paper. Still, there are few LCA studies related to the carbonization and liquefaction processes. Fast pyrolysis of

lignocellulosic biomass is widely studied compared to other types of pyrolysis. Therefore, more comprehensive comparative assessments of all thermochemical conversion technologies should be done.

The main limitation of current LCA studies is the lack of comparative assessment of different pathways based on environmental metrics. This is because different kinds of lignocellulosic biomass, different thermochemical pathways, and different end products are considered by various authors. The system boundaries also vary according to the requirement of the LCA framework (start to end point) and data availability. Different softwares are available for an LCA, and their databases vary depending on geographical location, climate, and process. Generally, outputs of impact assessments are reported in terms of functional units, which also have been found to differ in the reviewed studies. Therefore the development of a standardized approach is needed for a meaningful LCA comparison.

Among the environmental effect categories, global warming potential is most stressed by different authors. But a complete LCA analysis should consider all three impact assessment categories (human health, eco system, and resource depletion). Direct land use change has been studied by a few authors, but indirect land use change is not a consideration in any of the reviewed papers. Therefore, including indirect land use change may be done in future.

Fertilizer production and application are key contributors to global warming. Therefore plant species that require low maintenance and low agrochemical inputs need to be developed. Nowadays a number of policies encourage the use of biofuels instead of fossil fuels in

order to reduce the environmental impacts from the use of fossil fuels. Therefore a standardized method that will give a common field of comparison among the end products from different pathways is needed.

Based on our observations, the selection of technologies is highly dependent on the feedstock used, end products, and geographical location. Therefore more techno-economic assessments on the comparison of different formation pathways for a single product and a focus on product co-generation would be useful in future work. Even though biomass is a renewable resource, it produces GHG emissions, albeit comparatively lower than those of fossil fuels, during the whole life cycle of the conversion process. Therefore more research is required to optimize the process conditions and reduce the consumption of fossil fuels during thermochemical conversion.

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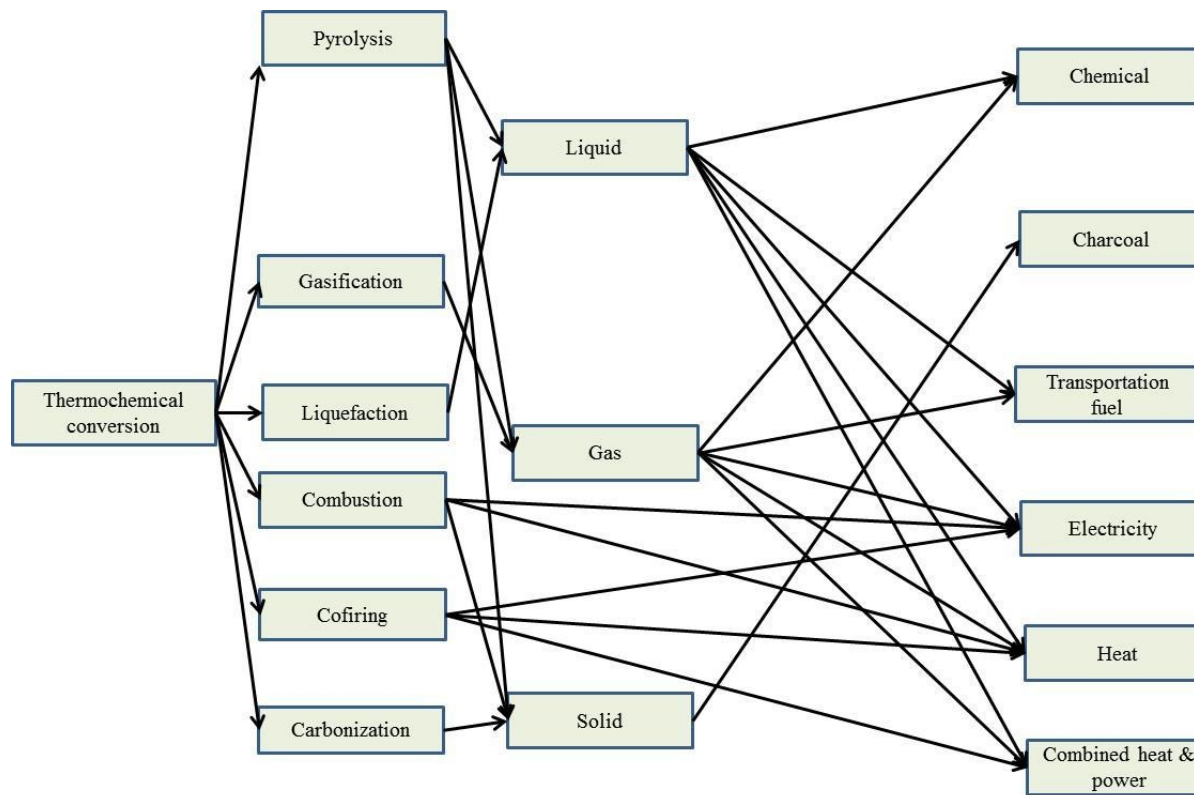
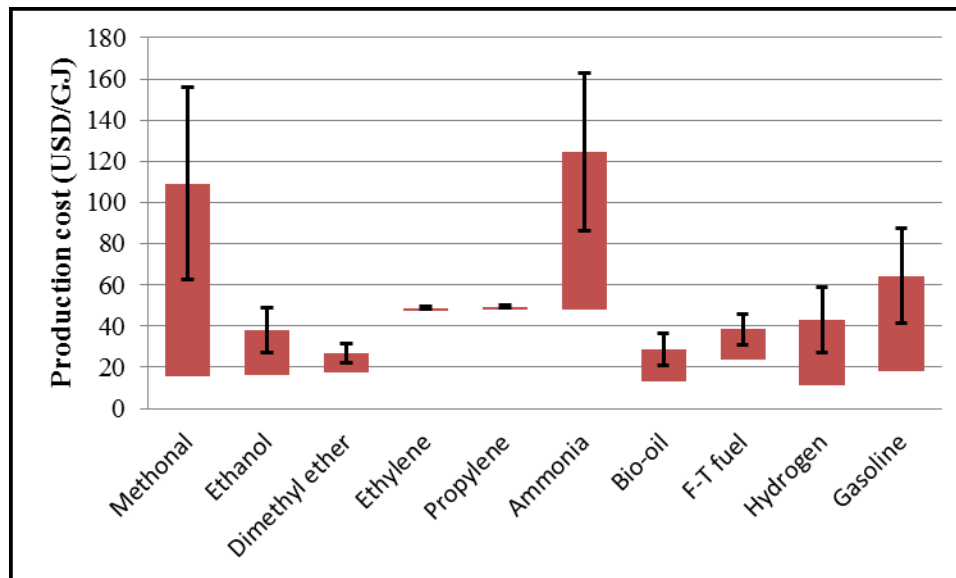**Figure 1. End products from thermochemical conversion**

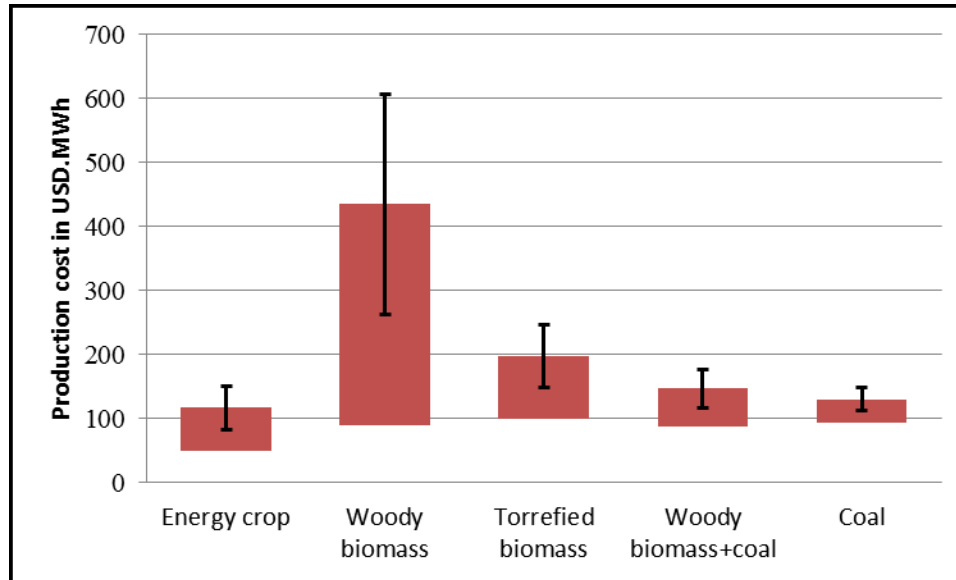**Figure 2. Comparison of chemical/fuels production cost**

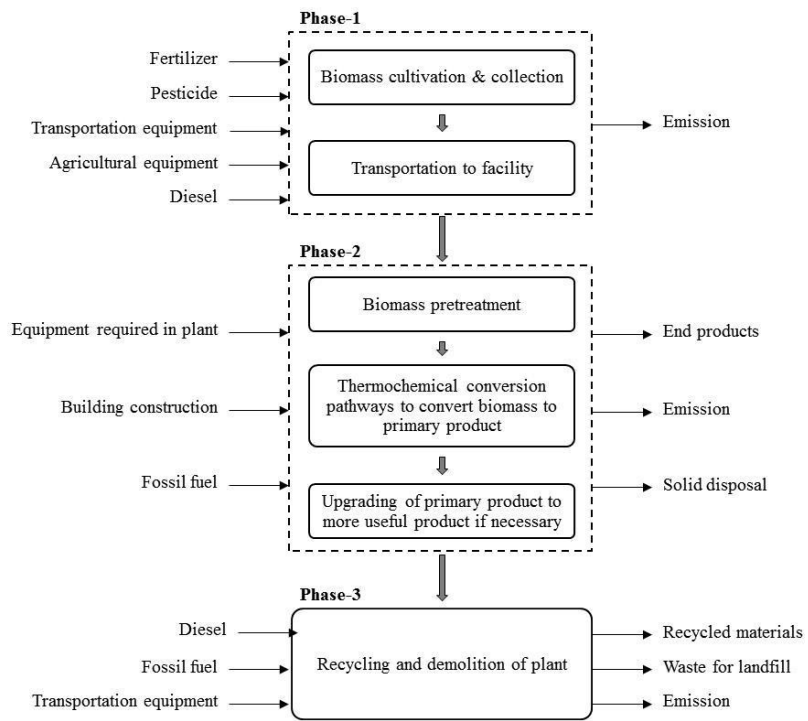**Figure 3. Production cost of power from different feedstock**

Figure 4. Generalized system boundary for an LCA analysis

Table 1. Summary of thermochemical technologies for biomass conversion.

Conversion Technology	Process Condition	Reactor types	Product yield			Reference
Pyrolysis			Liquid (wt%)	Gas (wt%)	Solid (wt%)	
Fast Pyrolysis	Atmospheric pressure, small particle size (< 3mm), short residence time (0.5-2s), moderate temperature (400-550^{0}C) in absence of oxygen	Fixed bed reactor, Tubular reactor, Bubbling fluidized bed reactor, Circulating fluidized bed reactor, Ablative Pyrolyzer, Rotating Cones reactor, Auger reactor, Cyclone reactor	65-75	13-25	12-19	[14, 15]
Slow pyrolysis	Low heating rate, moderate temperature (350-750^{0}C), atmospheric pressure, long residence time in absence of oxygen		30-50	15-30	30-60	[16, 17]
Intermediate Pyrolysis	Moderate temperature (<500^{0}C), moderate vapor residence time (4-10s) and atmospheric pressure		45-55	25-35	15-25	[18]
Flash Pyrolysis	Rapid heating (<0.5s), very small particle sizes (<0.5mm), temperature (400-1000^{0}C)		60-70	10-15	15-25	[19, 20]
Vacuum Pyrolysis	Moderate temperature (300-500^{0}C), pressure below atmospheric (<50kPa)		45-60	17-27	19-27	[21-23]
Ablative Pyrolysis	Moderate temperature (450 -600^{0}C), atmospheric pressure, particle size <		60-80	6-10	12-20	[24]

	3.5mm					
Gasification						
Hydrothermal gasification	Moderate to high temperature (600-1200^{0}C), presence/absence of catalyst, small particle size desirable, gasifying agent	Fixed bed, moving bed, fluidized bed and entrained flow gasifier	Gas yield (m^3 gas/kg biomass): 1-2.6			[8, 25, 26]
Combustion	Maximum temperature: 740-1300^{0}C, Air mass flow: 0.1-0.5 kg/m^2.s	Fixed bed, fluidized bed, circulating bed and entrained flow bed combustor	Power and heat			[27]
Liquefaction			Liquid (wt%)	Gas (wt%)	Solid (wt%)	
Hydrothermal/thermochemical liquefaction	Temperature: moderate to high (250-550^{0}C), pressure: 5-25 MPa, solvent type, heating rate: 5-140^{0}C/min	Parr high pressure reactor	60 -75	15-20	8 - 20	[11]
Carbonization	Temperature: low to high: (400-1200^{0}C), heating rate: 4-5 ^{0}C	Stainless steel container inside a furnace	Bio-char (wt%): 20 -35			[28]
Co-firing	%wt of biomass: 5 -20	Boiler	Power and heat			

Table 2. Comparison of the production costs of chemicals/fuels from different biomass thermochemical conversion technologies.

Bio-product	Feedstock	Location	Technology	Capacity (dry tonnes/day)	Base year	Production cost	Reference
Methanol	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	2000	2008	$0.29/kg $0.23/L $14.48/GJ	[30]
	Forest residue	Western Canada	Pressurized gasification + upgrading	2000	2008	$0.45/kg $0.36/L $22.67/GJ	[30]
	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	3000	2008	$0.28/kg	[30]
	Maize residue	South Africa	Gasification + methanol synthesis using superconverter	10-2000MW (thermal)	2008	$30.4-83.7/GJ	[31]
	Pine	Ithaca, USA	Gasification at 800°C + methanol synthesis	500-9600	2012	$15-32/GJ	[32]
	Pine	Ithaca, USA	Pyrolysis at 450°C + methanol synthesis	500-9600	2012	$25-48/GJ	[32]
	Pine	Ithaca, USA	Pyrolysis at 300°C + methanol synthesis	500-9600	2012	$55-105/GJ	[32]
Ethanol	Agricultural Biomass	Almería, Spain	steam–air indirect circulating fluidized bed gasification + upgrading	2140	2010	$0.95/kg	[33]
	Agricultur	Karlsruhe,	Fast pyrolysis + gasification + upgrading	600	2008	$14.4/GJ	[34]

	al Biomass	Germany					
	Natural gas	Karlsruhe, Germany			2008	$9.06/GJ	[34].
	Coal	Karlsruhe, Germany			2008	$6.18/GJ	[34].
Dimethyl ether	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	2000	2008	$0.47/kg $0.31/L $16.34/GJ	[30]
	Forest residue	Western Canada	Pressurized gasification + upgrading	2000	2008	$0.69/kg $0.45/L $23.71/GJ	[30]
	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	3500	2008	$0.44/kg	[30]
Ethylene	Lignocellu losic biomass	Karlsruhe, Germany	Gasification syngas-DME-Ethylene		2010	$2.068-2.126 /kg [a]	[35]
Propylene	Lignocellu losic biomass	Karlsruhe, Germany	Gasification syngas-DME-Propylene		2010	$2.032-2.089 /kg [a]	[35]
Ammonia	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	2000	2008	$2.09/kg $1.42/L $110.76/GJ	[30]

	Forest residue	Western Canada	Pressurized gasification + upgrading	2000	2008	$2.72/kg $1.86/L $98.57/GJ	[30]
	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	3000	2008	$2.06/kg	[30]
Bio-oil	Energy crops	UK	Fast pyrolysis	100-800	2009	$11.94-25.87/GJ [b]	[36]
Bio-char	Pine	Ithaca, USA	Slow pyrolysis		2012	$0.22-0.28/kg	[32]
Fischer-Tropsch fuel	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	2000	2008	$0.97/kg $0.78/L $21.79/GJ	[30]
	Forest residue	Western Canada	Pressurized gasification + upgrading	2000	2008	$1.53/kg $1.22/L $34.08/GJ	[30]
	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	4000	2008	$0.94/kg	[30]
Hydrogen	Forest residue	Western Canada	Battelle Columbus Laboratory (BCL) gasifier	2000	2008	$1.17/kg $9.75 /GJ	[37]
	Straw	Western Canada	Battelle Columbus Laboratory (BCL) gasifier	2000	2008	$1.29/kg $10.75/GJ	[37]
	Forest residue	Western Canada	Gas Technology Institute (GTI) gasifier	2000	2008	$1.3/kg $10.92/GJ	[37]

	Straw	Western Canada	Gas Technology Institute (GTI) gasifier	2000	2008	$1.33/kg $11.04 /GJ	[37]
	Whole tree	Western Canada	Gas Technology Institute (GTI) gasifier	2000	2008	$1.32/kg $11/GJ	[37]
	Whole tree	Western Canada	Fast pyrolysis + steam reforming	2000	2008	$2.40/kg $20 /GJ	[38]
	Forest residue	Western Canada	Fast pyrolysis + steam reforming	2000	2008	$3.00/kg $25/GJ	[38]
	Straw	Western Canada	Fast pyrolysis + steam reforming	2000	2008	$4.55/kg $38/GJ	[38]
Gasoline	Lignocellulosic biomass	Karlsruhe, Germany	Gasification syngas-DME-Gasoline		2010	$1.455-1.500/L [a] $52.83-53.63/GJ [a]	[35] [39]
	Coal	Karlsruhe, Germany	Gasification syngas-DME-Gasoline		2010	$0.970/L [a]	[39]
	Lignocellulosic biomass	Karlsruhe, Germany	Gasification syngas-FT synthesis-Gasoline		2010	$1.593-1.638/L [a]	[39]
	Coal	Karlsruhe, Germany	Gasification syngas-FT synthesis-Gasoline		2010	$1.004/L [a]	[39]
	Woody biomass	Golden, USA	Gasification syngas-methanol-Gasoline	2000	2007	$0.52/L $15.73/GJ	[40]

Liquefied petroleum gas (LPG)	Woody biomass	Golden, USA	Gasification syngas-methanol-LPG	2000	2007	$0.40/L $15.73/GJ	[40]
Diesel	Lignocellulosic biomass	Karlsruhe, Germany	Gasification syngas-FT synthesis-diesel		2010	$1.593-1.638 /L [a]	[39]
	Coal	Karlsruhe, Germany	Gasification syngas-FT synthesis-diesel		2010	$1.004 /L [a]	[39]
gasoline & diesel	Woody biomass	Ames, USA	Mild catalyst pyrolysis	2000	2011	$0.975/L	[41]
	Woody biomass	Ames, USA	Mild catalyst pyrolysis with cogeneration of electricity and hydrogen	2000	2011	$0.8/L	[41]
	Stover	Ames, USA	Fast pyrolysis + hydroprocessing	2000	2011	$0.68/L	[42]
	Corn stover	Ames, USA	Gasification + Fischer-Tropsch synthesis and hydroprocessing	2000	2007	$1.06-1.32/L	[43]
naphtha & diesel	Corn stover	Ames, USA	Fast pyrolysis + upgrading, with hydrogen generation on-site	2000	2007	$0.82/L	[44]
	Corn stover	Ames, USA	Fast pyrolysis + upgrading, with merchant hydrogen	2000	2007	$0.56/L	[44]

[a] the price in the reference is in € and was transferred into US$ with an average exchange rate of 1€=1.3$ in 2010.

[b] the price in the reference is in £ and was transferred into US$ with an average exchange rate of 1£=1.567$ in 2009.

Table 3. Comparison of the production cost of electricity from different biomass thermochemical conversion technologies.

Feedstock	Location	Technology	Power output (MWe)	Base year	Production cost ($/MWh)	Reference
Energy crop	UK	Organic Rankine cycle based CHP system	0.15	2013	47-59 [a]	[45]
Energy crop	UK	Biomass gasification (downdraft gasifier) based CHP system	0.15	2013	102-114 [a]	[45]
Woody biomass + Coal	The Netherlands	Supercritical pulverized coal-fired (PC) boiler	500	2011	81.9-125.6 [b]	[46]
Woody biomass + Coal	The Netherlands	Supercritical circulating fluidized bed (CFB) boiler	500	2011	84.6-137.9 [b]	[46]
Woody biomass	The Netherlands	Subcritical CFB boiler	250	2011	163.8-300.3 [b]	[46]
Woody biomass	The Netherlands	Subcritical bubbling circulating bed (BFB) boiler	75	2011	232.0-409.5 [b]	[46]

Torrefied biomass	The Netherlands	IGCC without CO_2 capture		2008	88.6-128.1 [c]	[47]
Torrefied biomass	The Netherlands	IGCC with CO_2 capture		2008	126.0-175.1 [c]	[47]
Coal	The Netherlands	IGCC without CO_2 capture		2008	83.3 [c]	[47]
Coal	The Netherlands	IGCC with CO_2 capture		2008	115.3 [c]	[47]
Biomass	UK	Fast pyrolysis, diesel engine	1-20	2002	70-140 [d]	[1]
Biomass + Natural gas	Brazil	Indirect co-firing of biomass derived gas with natural gas	150	2003	59	[48]
Biomass	Brazil	Biomass sole plant	24	2003	94	[48]

[a] the price in the reference is in £ and was transferred into US$ with an average exchange rate of 1£=1.575$ in 2013.

[b] the price in the reference is in € and was transferred into US$ with an average exchange rate of 1€=1.365$ in 2011; the lower number in the range shows the price without CO_2 capture, and the higher number shows the price with CO_2 capture.

[c] the price in the reference is in € and was transferred into US$ with an average exchange rate of 1€=1.388$ in 2008.

[d] the price in the reference is in € and was transferred into US$ with an average exchange rate of 1€=0.96$ in 2002.

Table 4: Summary of the LCA of different thermochemical conversion technologies.

Process	Feedstock	End product	Boundary	Functional unit	Environmental impact categories	Comment	Reference
Co firing	Rice straw	Power	Phase 1 and 2	1 MWh	Acidification, global warming potential (GWP), eutrophication, human toxicity	Significant reduction in impact categories @ 5% biomass co-firing condition	[66]
	Willow	Electricity	Phase 1 and 2	1 MWh	Net energy ratio and net global warming potential	Net energy ratio increased by 9% and net global warming potential decreased by 7 - 10% at 10% co firing. GWP: 910 kg CO_2 eq/MWh	[67]
	Wood residue	Electricity	Phase 1, 2 and 3	1 kWh	Global warming potential	GWP: 894.3 g CO_2 eq/ kWh @ 15% co-firing - 1002.9 g CO_2 eq/ kWh @ 5% co-firing	[57]
	Energy crop	Electricity	Phase 1, 2	1TJ	Global warming potential	GWP: 298 ton CO_2 eq/TJ @ 10% Direct	[10]

	and wheat straw		and 3			co-firing GWP: 300 ton CO_2 eq/TJ @ 10% indirect co-firing Coal boiler efficiency and biomass treatment are important parameters.	
Pyrolysis							
Fast pyrolysis	Corn stover	Bio gasoline	Phase 1 and 2	1 ha	Global warming potential	GWP: 7.65 ton CO_2 eq/ha Corn stover removal rate is the sensitive parameter that affects the bio-char and bio-oil yield.	[68]
	Short rotation poplar	Gasoline, diesel, and char	Phase 1 and 2	1 MJ	Cumulative energy demand, global warming, ozone layer depletion, photo chemical oxidant formation, land competition, acidification, eutrophication	GWP: -50.54 kg CO_2 eq/MJ Biomass pretreatment, pyrolysis, and steam reforming are the main contributors in the environmental impact categories.	[14]
	Forest residue	Gasoline and diesel	Phase 1 and 2	1 km	Global warming potential and net energy value (NEV)	GWP: 98-117 g CO_2 eq/km NEV: 0.92-1.09 MJ/km GWP and NER are lower than the conventional gasoline and diesel	[58]
	Corn stover	Gasoline	Phase 1 and 2	1 MJ	Global warming potential	During upgrading of biofuel by hydroprocessing: GHG emissions reduction is maximized when hydrogen is	[69]

						produced from bio-oil reforming	
	Logging residue, hybrid poplar, willow, and waste wood	Electricity	Phase 1 and 2	1 kWh	Global warming potential	Depending on the feedstock type, life cycle GHG savings of 77-99% estimated for power generation from pyrolysis oil to fossil fuel combustion	[70]
Ablative pyrolysis	Wood chip	Electricity	Phase 1 and 2	1 kWh	Global warming, ozone depletion, photochemical ozone creation potential, acidification, eutrophication	All impact categories are significantly decreased except eutrophication potential due to use of fertilizer during cultivation	[61]
Slow pyrolysis	Corn stover and switch grass	Bio-char	Phase 1 and 2	1 tonne of dry biomass	Global warming potential	GWP for corn stover: -864 kg CO_2 eq/ tonne of dry biomass GWP for Switchgrass: +36 kg CO_2 eq/ tonne of dry biomass	[59]
Flash pyrolysis	Wood waste	Biofuel and power	Phase 1 and 2		Global warming, ozone layer depletion, photo chemical smog, acidification, eutrophication, ecotoxicity, human toxicity	Emission from combustion of bio-oil has effect on GWP, acidification, human toxicity and eutrophication	[71]
Gasification	Forest residue	Heat and power	Phase 1 and 2	1 MJ	Global warming, ozone layer depletion, photo chemical oxidization, acidification,	GWP: 8.8 -10.5g CO_2 eq/MJ Environmental impacts are significant for the biomass procurement and plant	[72]

				eutrophication, toxicity, abiotic depletion	operation	
	Poplar energy crop	Electricity	Phase 1, 2 and 3	1 MWh	Global warming, ozone layer depletion, smog, acidification, eutrophication, solid waste, energy consumption	Most negative environmental effects are caused by the use of chemicals and fertilizer	[73]
	Willow biomass	Heat and power	Phase 1&2	1 MWh	Fossil energy requirement, primary energy requirement, land use, global warming potential, acidification	Significant reduction in GHG emissions from willow biomass to the fossil fuel based systems	[74]
	Biomass	Hydrogen	Phase 1, 2 and 3	1 MJ	Global warming, smog, acidification, eutrophication, carcinogenesis, heavy metals, smog	Among LCA studies for two pathways of hydrogen production, biomass gasification-steam reforming-PSA route is the energy efficient one, and biomass-gasification-electricity-electrolysis has better environmental performance	[60]
Combustion	Birch wood	Heat	Phase 1 and 2	1 kWh	Global warming, photochemical oxidation, acidification, eutrophication,	GWP: 80 -110 g CO_2 eq/ kWh Comparing the LCA analysis of new stove technology to old one, the former has the better environmental impact	[75]
	Rice husk	Electricity	Phase 1 and 2	1 MWh	Global warming, acidification, eutrophication,	GWP: 217.33 kg CO_2 eq/MWh	[76]

				ecotoxicity		
Forest residue	Power	Phase1, 2 and 3	1 kWh	Global warming	GWP: 11 - 14g CO_2 eq/kWh Emission and energy consumption depends on the moisture content and the heating value of biomass	[77]
Wood waste	Electricity	Phase 1 and 2	1 MJ	Global warming, respiratory effect, photo oxidant formation, acidification, eutrophication,	Inventory data collection is the major factor for LCA analysis	[78]