Advances and Trends in Woody Biomass Gasification

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Abstract

Renewable energy technologies can assist countries meet their policy demands for secure, reliable and affordable energy through broadening electricity access and stimulating development. Among available sources biomass can play a major role for the development of sustainable energy system.

This study assesses the techno-economic potential of gasification technologies for electricity production using residual woody biomass as the feedstock. The state-of-the-art electrical efficiencies of selected biomass gasification technologies were extensively investigated. Comprehensive study was conducted for the economic characterization of selected technologies paying special emphasis on investments, costs of operation and maintenance, fuel costs etc. The integrated economic analysis was carried out based on the levelized costs of energy generation (LCOE) method.

The main outcome includes selection of suitable technology for a biomass based plant at specific capacity range from techno-economic points of view. Study showed that for small-scale plants the most efficient technology is internal combustion engine coupled to a gasification unit. For medium to large scale plants gas or steam turbines perform better. Most favorable technology with respect to economic and energy provisions are BIGCC plants. Results include for DG/GE plants with scale range 0.01-3 MW_e the LCOE range is 10.39-25.46 $ctEUR/kWh_e$, for FBG/GE plants with scale range 2-20 MW_e the LCOE range is 9.09-27.15 $ctEUR/kWh_e$, and for BIGCC plants with scale range 6-300 MW_e the LCOE range is 6.30-17.49 $ctEUR/kWh_e$.

Finally, a mathematical tool was developed for the techno-economic evaluation of biomass gasification based power plants and study cases were conducted to precisely estimate the key parameters of economic performance.

Keywords:
Biomass, Fixed bed gasification, Fluidized bed gasification, BIGCC, Electrical efficiency, LCOE.

Resumo

Tecnologias de energia renovável podem ajudar países a cumprir as suas metas para uma energia segura, fiável e economicamente viável através de um diverso acesso à electricidade e desenvolvimento estimulante. De entre as fontes disponíveis, a biomassa pode ter um papel significante para o desenvolvimento de um sistema sustentável de energia.

Este trabalho avalia o potencial tecnoeconómico de technologias de gasificação para produção de electricidade através do uso de madeira residual como fonte de alimentação. O estado de arte de eficiências eléctricas de determinadas technologias de gasificação de biomassa foram extensivamente investigadas. Um estudo compreensivo foi feito para a caracterização económica das tecnologias selecionadas, dando especial enfase nos investimentos, custos de operação e manutenção, custos de combustíveis, etc. A análise económica integrada foi feita com base no método de custos nivelados de geração de energia (LCOE em inglês).

Os principais resultados incluem a seleção adequada de tecnologias para uma central de biomassa com capacidade específica do ponto de vista tecno-económico. O estudo mostrou que para centrais pequenas, a tecnologia mais eficiente é o acoplamento de motores de combustão interna com uma unidade de gasificação. Para centrais médias ou grandes, turbinas de gás ou vapor têm melhores performances. A tecnologia mais favorável economicamente e de fornecimento de energia encontra se nas centrais BIGCC. Os resultados incluem para centrais DG/GE numa escala entre 0.01-3 MW_e, a variação de LCOE é de 10.39-25.46 $ctEUR/kWh_e$, para centrais FBG/GE com uma capacidade entre 2-20 MW_e, a variação de LCOE é de 9.09-27.15 $ctEUR/kWh_e$, e para as centrais BIGCC com uma capacidade entre 6-300 MW_e, a variação de LCOE é de 6.30-17.49 $ctEUR/kWh_e$.

Finalmente, uma ferramenta matemática foi desenvolvida para a avaliação tecno-económica da gasificação da biomassa baseada em centrais e casos de estudo foram realizados para estimarem precisamente os parametros chave da performance económica.

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List of Abbreviations

LCOE	Levelized Costs of Energy Generation
ICE	Internal Combustion Engine
BIGCC	Biomass Integrated Gasification Combined Cycle
DG/GE	Downdraft Gasification/Gas Engine
MW_e	Mega-Watt of Electric Power
FBG/GE	Fluidized Bed Gasification/Gas Engine
ctEUR	cent European Euro
kWh_e	kilo-Watt hour of Electrical Energy
GHGs	Green House Gases
CO_2	Carbon Dioxide
IEA	International Energy Agency
Mtoe	Million tonnes of oil equivalent
OECD	Organization for Economic Co-operation and Development
Mboe	Million barrels of oil equivalent
EJ	Exa-Joule
Gtoe	Billion tonnes of oil equivalent
y	Year
t	Metric tonnes
h	Hours
MWh_e	Mega-Watt hour of Electrical Energy
EURELECTRIC	Union of the Electricity Industry in Europe
IRENA	International Renewable Energy Agency
HHV	Higher Heating Value
MJ	Mega Joules
kg	kilogram
LHV	Lower Heating Value
TWh_e	Terra-Watt hour of Electrical Energy
EU	European Union
GW_e	Giga-Watt of Electric Power
syngas	Synthesis gas/producer gas
η_e	Electrical Efficiency
η_{th}	Thermal Efficiency
ORC	Organic Rankine Cycle
CHP	Combined Heat and Power
R	Reactions
SNG	Synthetic Natural Gas
Nm^3	Normal cubic meter (Temperature: 0^oC , Pressure: 1atm)

kW_{th}	kilo-Watt of Thermal Power
MW_{th}	Mega-Watt of Thermal Power
kW_e	kilo-Watt of Electric Power
BFB	Bubbling Fluidized Bed
CFB	Circulating Fluidized Bed
IGCC	Integrated Gasification Combined Cycle
MSW	Municipal Solid Waste
GT	Gas Turbine
GE	Gas Engine
UG	Updraft Gasification
O&M	Operation and Maintenance
NEA	Nuclear Energy Agency
TPC	Total Plant Cost
CAPEX	Capital Expenditures
SI	Specific Investments
CEPCI	Chemical Engineering Plant Cost Index
USD	United States Dollar
GBP	Great Britain Pound
SEK	Swedish Krona
EUR	European Euro
OPEX	Operational Expenditures
MWh_{th}	Mega-Watt hour of Thermal Energy

1. Introduction

A reliable, affordable and sustainable clean energy supply is of major importance for society, economy and the overall environment and this will turn out to be compelling in the 21st century. It is becoming increasingly difficult to ignore the effects of global warming due to the burning of fossil fuels and it is being observed as a key point of research among the scientists around the world (Shafie, 2012). Reportedly, energy production is the leading source of CO_2 and other GHGs, and approximately 70% of all GHG emissions are emanated by the energy sector (Hook, 2013). In addition to that the high depletion rate of fossil fuel reserves motivates the government policy makers to shift the energy policy towards the other non-conventional sources of energy (Kumar, 2009; Nel, 2009). At present, renewable energy technologies are one of the most widely used sources instead of the conventional fuels in four recognizable areas: electricity generation, space heating, transport fuels and rural off-grid energy services (Kirkels, 2011).

Compared with other renewable energy options like solar and wind, biomass is considered as the renewable energy source that has the highest potential to contribute to the energy demands of modern society for both the developed and developing economies worldwide (IEA, 2006; Kaygusuz, 2009). Energy from biomass based on residues from agriculture, forestry and other energy crops, wood, byproducts from processing of biological materials, and organic parts of municipal and sludge wastes can contribute significantly towards the objectives of Kyoto agreement in lessening the greenhouse gas emissions and to the problems associated with climate change (Fiorese, 2014; Demirbas, 2009; Kumar, 2009). Biomass can be stored and energy can be produced on requirement that permits a controllable supply which is a distinct advantage over the use of other renewable energy sources, like solar and wind power, which are confined because of intermittency during power generation (Fiorese, 2014; Kirkels, 2011). The energy supply from solar and wind technology can be predicted but cannot be controlled as a result these renewable sources need a backup generation plant to counterbalance that period of time when sunshine or wind is unavailable. Biomass and biofuels can be availed as replacements for fossil fuels in generating heat, electricity, and producing liquid and gaseous fuels, bringing benefits such as sustainability, regional economic development, social and agricultural development, and an unvarying supply of energy with slight amount of emissions (Demirbas, 2007; Kaygusuz, 2009; Kumar, 2009).

The ampleness of biomass levels it as the third ranked energy resource after oil and coal (Pereira, 2012). But the estimates of potential global biomass energy vary significantly in literature and the use of biomass resources differs notably by region (Kumar, 2009). In Africa 47.8% of the 2010 total primary energy supply attained from biomass ca. 328 Mtoe of 686 Mtoe, while in OECD countries the corresponding figure was 4.5% i.e. 242 Mtoe out of 5406 Mtoe (IEA, 2012a). During 1991, biomass contributed approximately 14% of the world's primary energy which is equivalent to around 25 Mboe/day or 55 EJ of energy (Hall, 1991). In mid-2011, a world population of 7 billion people consumes around 13 Gtoe/y of primary energy (Dahmen, 2012). The world primary energy mix consists of ca. 80% fossil fuels and ca. 10% bioenergy as shown in Figure 1 (Dahmen, 2012). Towards the end of the century, an increase of the world population to a maximum of almost 10 billion is expected in combination with a doubling of the energy consumption to about 25 Gtoe/y (Dahmen, 2012).

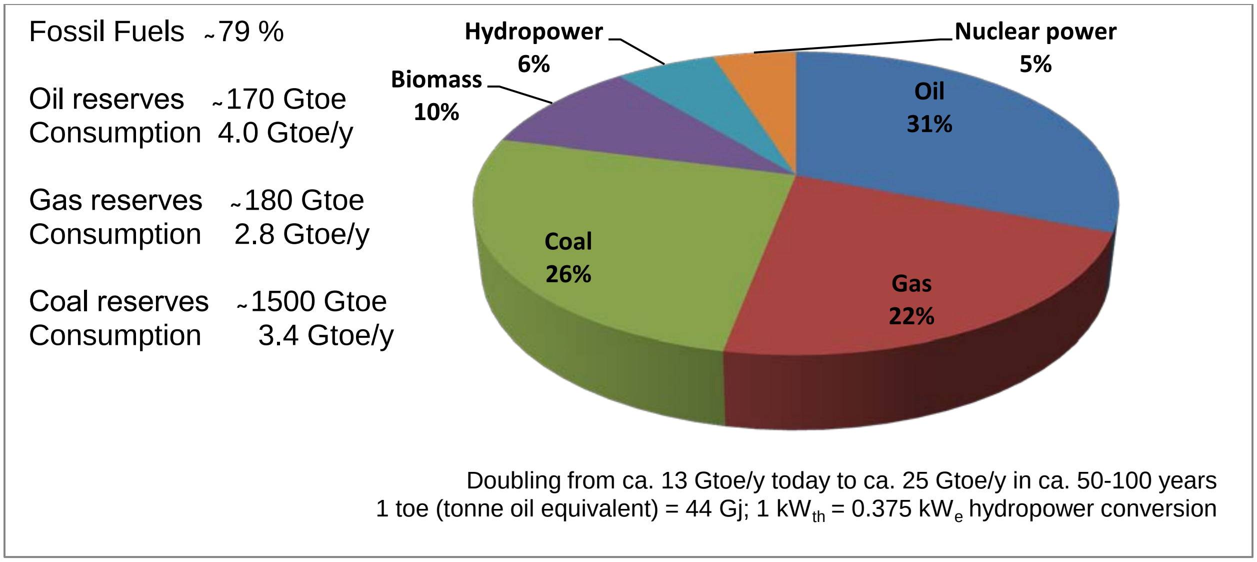


Figure 1 World primary energy mix 2010 (Source: Adapted from Dahmen, 2012)

As far as thermochemical energy conversion is concerned, biomass can be handled through three different processes: gasification, pyrolysis, and direct combustion, with gasification being the most influential process with higher electrical efficiencies in generating electricity and lower emissions compared to other technologies (i.e. fast pyrolysis, combustion etc.) (Purohit, 2009; Roos, 2010; Pereira, 2012). Gasification method has been able to attract worldwide attention for advanced applications in biomass-to-energy conversions due to its varied uses and benefits (Asadullah, 2014). Gasification is a clean and highly proficient conversion process that offers the possibility to convert various biomass feedstocks to a wide variety of applications, as shown in Figure 2 (Kirkels, 2011).

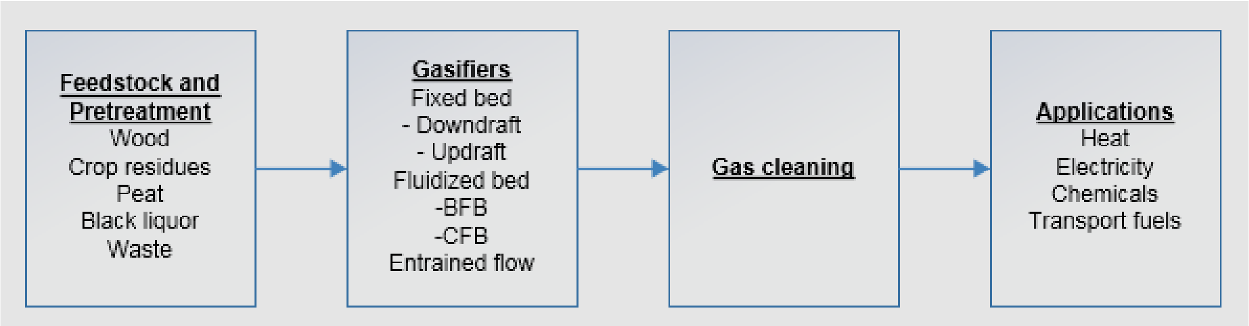


Figure 2 Flexibility of gasification technology in advanced applications (Source: Kirkels, 2011)

Gasification technology can be used in different energy fields such as for the generation of heat, production of hydrogen and ethanol, and power generation in developed countries, as well as for decentralized rural electrification in developing countries (Pereira, 2012). Intrinsically, it has been considered the enabling technology for modern biomass use (Kirkels, 2011). The generation of electricity using gasification technologies has been started operating in several parts of the world for the reduction of greenhouse gas emissions (Pereira, 2012; Asadullah, 2014). In rural areas, particularly in remote locations, transmission and distribution of energy generated from fossil fuels can be difficult and expensive, which is a challenge that biomass energy generation can attempt to defend. In many developing countries biomass is now one of the most important source of energy, for example, India has reached ca. 70 MW_e from small-scale biomass gasification plants for the generation of electricity in remote locations. Currently, biomass fulfills 70% of the basic energy needs in these rural areas, which cover almost 70% of India's population (Liming, 2009). In Bangladesh, small-scale rice husk gasifier based power plant started operating since 2007, and the total estimated technical potential of power production is 171 MW_e (Huda, 2014).

There is a constant and consistent interest for the production of electricity from biomass through gasification (Kirubakaran, 2009). However, due to the lack of technical and economic feasibility studies of implementation of available gasification technologies, biomass is unable to play a big role in energy generation sector and at present biomass has a small share of the electricity production in developed countries (Kirkels, 2011). This study aims to conduct a proper technical review of the feasible technologies for gasification. It evaluates the available technologies focusing specifically on fixed bed and fluidized bed gasifier technologies with respect to electrical efficiencies, potential scaling effects, and investments based on information published in different databases and articles in the 0.01-300 MW_e range. It is observed that scale effects have a great significance on overall efficiencies and specific investments of the plants.

The main goal of this study is to provide a techno-economic analysis which could be useful for making a decision when a new biomass power plant will be considered to construct for a certain capacity. Based on the information about the available woody biomass resources the selection of a competitive technology among the options will be made using the mathematical tool that has been developed during this work. An extensive sensitivity analyzes are made to scrutinize energy generation costs for several conditions and input parameters. Finally, this study presents a comprehensive analysis of selected biomass gasification technologies which is useful to identify a competitive biomass-to-power system from cost of energy generation point of view.

1.1 Motivation

The generation of energy applying biomass gasification processes may sound like a recent technology, but in reality it has over 100 years of existence. History shows that our forefathers were experts in using fire from the existing biomass. Progressively, means for converting biomass into biofuel or straightly into energy by direct combustion processes were developed which are useful and efficient (Pereira, 2012).

During the world wars, when oil was scarce for utilization, efforts related to thermo-chemical biomass conversion was stimulated. After WWII, however, biomass research was suppressed for some time due to the low prices of fossil fuels. Nevertheless, with the news of the exhaustion of oil reserves and natural gas in recent decades along with the growth in costs of fossil fuels and the concerns with the emission of pollutant gases, research activities in thermal conversion of biomass have been accelerated (Roos, 2010; Pereira, 2012).

In order to mitigate the rate of GHGs emission the energy sector is now turning into renewable technologies, and in this context, electricity production using gasification techniques can play a significant role (Son, 2011; Kirkels, 2011). Additionally, the local economic development of rural areas is possible through far-reaching renewable energy deployment provided that there are adequate financial incentives, subsidies, and reinforcement of the infrastructure from the governments (Liming, 2009). In short, biomass gasification technologies can be used for energy generation purposes but investments in research and development in this area have been small, and the economic feasibility of these technologies have not been well enough investigated and disseminated. This is the primary reason why this study sought to make a contribution in techno-economic assessment of biomass gasification technologies for energy generation.

1.2 Statement of purpose

The main objective of this study is to technically and economically analyze the option of using residual woody biomass for energy generation by gasification at different scale ranges with special emphasis on the latest developments and international trends.

1.3 Research questions

To achieve the purpose the following research questions are needed to be addressed:

- Which are the technologies that are commercially available now for energy generation using biomass gasification?
- How much electricity can be generated given the amount of available woody biomass with the selected gasification technologies?
- What are the most important parameters for evaluating the economic performance of a biomass gasification plant?
- What are the approximate levelized costs of energy generation using the selected technologies?
- What is the most suitable technology among the options to set up a new plant with a specific scale range?

1.4 Assumptions

The following assumptions are applicable to this study:

- The data that are collected from different sources with respect to electrical efficiencies of selected biomass gasification technologies are reliable. Nevertheless, the consistency of the data is evaluated.
- The data that are accumulated from different sources with respect to specific invests, costs of operation and maintenance, fuel costs of the selected biomass gasification technologies are reliable. Nevertheless, the consistency of the data is evaluated.
- The total amount of available woody biomass resources on dry basis is known and the lower heating value of this feedstock on dry basis is also known.
- The sizes of the biomass based power plants are assumed to be small, medium, and large-scale range.
- The interest rate “d” which is used for discounting capital costs is stable and does not alter during the lifetime of the plant under consideration. In this study a discount rate of 10% is considered for calculation of LCOE.

- The cost of electricity or the selling price of produced electricity is stable and does not alter during the lifetime of the plants under consideration.
- It is assumed that the fuel price and the maintenance costs are not subject to a change within the lifetime of the plant. The fuel price assumed for residual woody biomass includes the costs of transportation and delivery to the plant site.

1.5 Limitations

The particular limitations identified in this study are:

- The study is limited to fixed bed and fluidized bed biomass gasification technologies. The co-firing and entrained flow technologies are not considered.
- Environmental performance evaluation is not done.
- Variable operating cost (EUR/MWh$_e$), such as cost of materials, is considered negligible during the calculation of levelized costs of energy generation (LCOE).
- Any supplementary costs such as carbon costs (EUR/t CO_2), decommissioning costs (EUR/MWh$_e$) are not included in the LCOE calculations.
- Labor costs are incorporated within O&M costs, and O&M costs are calculated as a fraction in relation to the specific investments.

1.6 Structure of the thesis

This thesis report is organized with five different chapters with distinct topics being described in each chapter. First of all, in the introductory chapter the key issues are mentioned such as the motivation and specific objectives of the thesis, and the assumptions and limitations of this study.

The next chapter is about the literature review of the biomass, the biomass conversion routes specifically gasification, and the available technologies for energy generation. This chapter shows the recent technological trends in this field.

In the following chapter, the research framework and methodology is explained. Here, the most important technologies are selected for assessment. Then, the LCOE method is explained in details with the associated parameters.

In chapter 4, data analyzes, calculations and key findings from the results are discussed. A comprehensive sensitivity analyzes result is included in association with appropriate input parameters. Two study cases are reviewed for different scale ranges at the end.

In the final chapter a conclusion with comments about the findings, implication of the thesis and the recommendations about the future work are discussed.

All the references that are being used during this thesis work and the necessary appendices are attached at the very end of the thesis report.

2. Literature Review

A comprehensive literature review was performed in order to get a solid understanding of the state of the art in the field of biomass gasification. Main topics covered were biomass and its products, biomass-to-energy conversion technologies with special focus on gasification techniques, operating conditions of selected technologies, and their merits and demerits.

2.1 Introduction to bioenergy

In the present situation of growing energy consumption throughout the world, the energy usage and sources have become a dominant issue with important connections in public policy, economic development, and environmental impacts. For the reason that the main source of energy generation that is fossil fuels, the reserves are depleting and the fuel price is increasing this hereby creating stress in economies of countries which are highly dependent on these energy sources (Roos, 2010). Besides, there are countries which have limited or even no availability of fossil fuel resources. However, biomass is available locally all over the world (Asadullah, 2014). Biomass can be treated as a source of energy input for electricity generation, heat supply, and in the production of liquid and gaseous fuels (Kumar, 2009). There exist a wide range of sources to obtain biomass in a variety of forms which have distinctive properties that impact their usefulness for energy generation purposes. Primarily, biomass can be derived from three major sources: forestry, agricultural products and biogenic wastes (EURELECTRIC, 2011). The availability and sustainability of the biomass feedstock is essential for a biomass based power plant's economics and environmental benefits. The most available feedstock can further be categorized as urban or rural (IRENA, 2012). These categories enclose a wide range of feedstocks, as presented in Table 1.

Table 1 Biomass feedstock (Source: IRENA, 2012; EURELECTRIC, 2011; Basu, 2010)

Rural	Urban
Forest residues and wood waste (e.g. firewood, wood chips, bark, branches, sawdust, stumps etc.)	Urban wood waste (e.g. packing crates, wood pallets, etc.)
Agricultural residues (e.g. corn stalks/stovers, rice husk, sugar beet, bagasse, wheat straw, etc.)	Wastewater and sewage biogas
Energy crops (e.g. herbaceous and annual growth materials such as *Miscanthus*, switch grass, Jatropha, rape seed, soybean, sugar cane, palm sunflower seed, beech wood etc)	Landfill gas
Biogas from livestock effluent	Municipal solid waste Food processing residues (commercial and household sectors)

There is a clear distinction between the primary feedstock and the final product for energy production in case of bioenergy as presented in Figure 3. Most forms of primary biomass feedstocks are subject to some sort of pre-processing to alter them into useful energy products. Energy densities, lack of uniformity, ash and moisture contents are some of the characteristics that affect the quality of biomass feedstock (IRENA, 2012, EURELECTRIC, 2011). These parameters have an impact on the cost of biomass feedstock per unit of energy, transportation, pre-treatment and storage costs, likewise the suitability of different conversion technologies (IRENA, 2012). It is mentioned in a study report that biomass for combustion and gasification purposes should have a low moisture level, more precisely in a range of 10-15% (Buragohain, 2010). Usually, biomass feedstock is very heterogeneous in nature and the chemical compositions are highly dependent on the originating plant species. This remarkable heterogeneous nature of biomass can be a problem despite some conversion technologies (e.g. combustion) can accept a wide range of biomass feedstock; but others (e.g. gasification) require substantial homogenous feedstock in order to operate properly (IRENA, 2012).

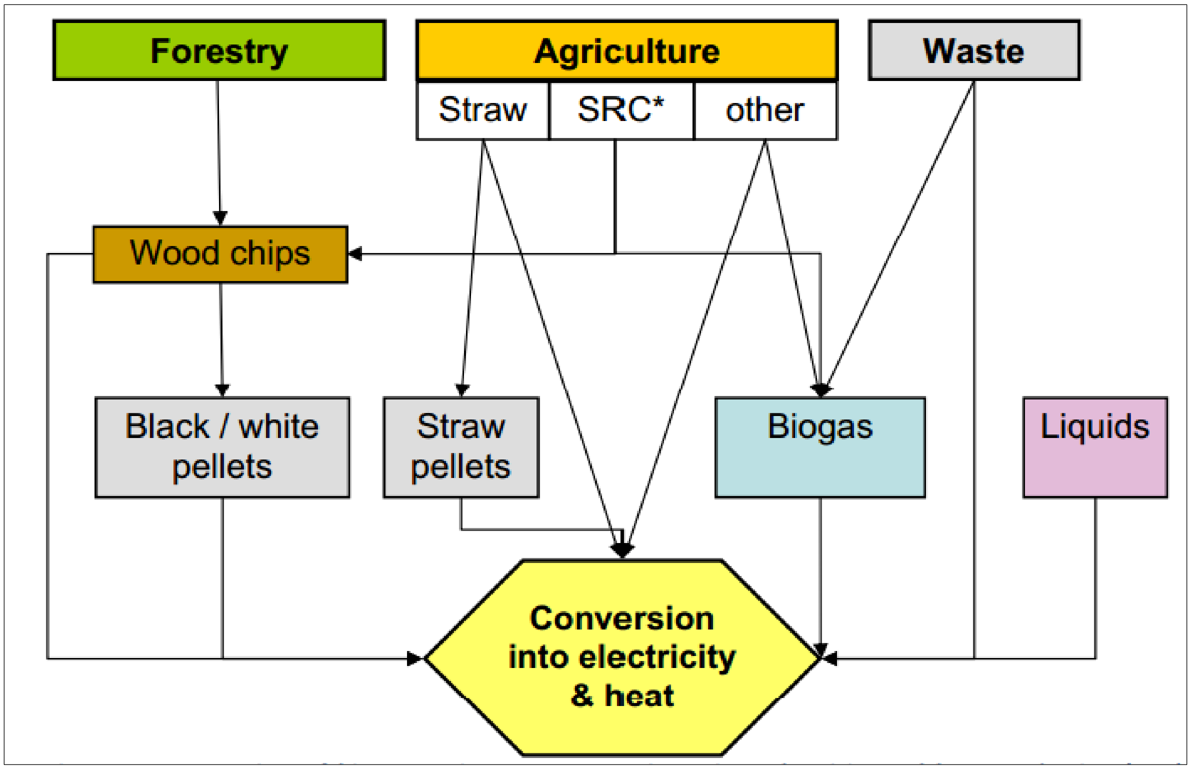


Figure 3 Overview of biomass primary resources input into electricity and heat production (SRC*- short rotation coppice) (Source: EURELECTRIC, 2011)

The chemical composition of the biomass feedstock controls its energy density. The energy density on a dry basis of different biomass feedstock is presented in Table 2 (IRENA, 2012). The moisture content of feedstock can vary from 10-60%, or even more in case of some organic wastes. But the higher value of moisture content corresponds to the lower energy potential. This in turn increases the transportation costs and the fuel cost per unit of energy production. In order to lower the transportation costs and improve the conversion efficiency the energy density of biomass feedstock need to be upgraded. The primary means of solving this issue is through drying by either natural or accelerated processes. Alternative ways include torrefaction, pelletising or briquetting, and conversion to charcoal (IRENA, 2012). Another important issue related to biomass feedstock is the ash content. Ash forms deposits inside the combustion chamber and gasifier which is called “slagging” and “fouling”. These can undermine the performance of the conversion process and also increase maintenance costs. Grasses, bark and agricultural crop residues usually have higher volume of ash compared to woody residues

(IRENA, 2012). In order to minimize the formation of slagging and fouling, the temperature of conversion process need to be kept at low enough level so that ash is prevented from fusing. Another way could be high temperature conversion process that allows the formation of clinkers (hardened ash) which are disposed of conveniently (IRENA, 2012).

Table 2 Heat content of various biomass fuels (dry basis) (Source: IRENA, 2012)

Types	Higher heating value (MJ/kg)	Lower heating value (MJ/kg)
Agricultural Residues		
Corn stalks/stovers	17.6 – 20.5	16.8 – 18.1
Sugarcane bagasse	15.6 – 19.4	15 – 17.9
Wheat straw	16.1 – 18.9	15.1 – 17.7
Hulls, shells, prunings	15.8 – 20.5	-
Herbaceous Crops		
Miscanthus	18.1 – 19.6	17.8 – 18.1
Switchgrass	18.0 – 19.1	16.8 – 18.6
Other grasses	18.2 – 18.6	16.9 – 17.3
Bamboo	19.0 – 19.8	-
Woody Crops		
Black locust	19.5 – 19.9	18.5
Eucalyptus	19.0 – 19.6	18.0
Hybrid poplar	19.0 – 19.7	17.7
Douglas fir	19.5 – 21.4	-
Poplar	18.8 – 22.4	-
Maple wood	18.5 – 19.9	-
Pine	19.2 – 22.4	-
Willow	18.6 – 20.2	16.7 – 18.4
Forest Residues		
Hardwood wood	18.6 – 20.7	-
Softwood wood	18.6 – 21.1	17.5 – 20.8
Urban Residues		
MSW	13.1 – 19.9	12.0 – 18.6
RDF	15.5 – 19.9	14.3 – 18.6
Newspaper	19.7 – 22.2	18.4 – 20.7
Corrugated paper	17.3 – 18.5	17.2
Waxed cartons	27.3	25.6

2.2 Overview on current situation of biomass power production

The use of biomass to produce electricity has steadily increased by an average of 13 TWh_e per year between 2000 and 2008 (Evans, 2010). Biomass based electricity has maintained ca. 2% market share of total global generation over the last 20 years (Evans, 2010). The use of biomass energy is widespread, as can be seen in Figure 4. There are ca. 62 countries in the world presently producing electricity from biomass (Evans, 2010). The USA is playing the dominant role in biomass electricity production sector with a share of around 26% of total world production, followed by Germany at 15%, Brazil and Japan both at 7% (Evans, 2010).

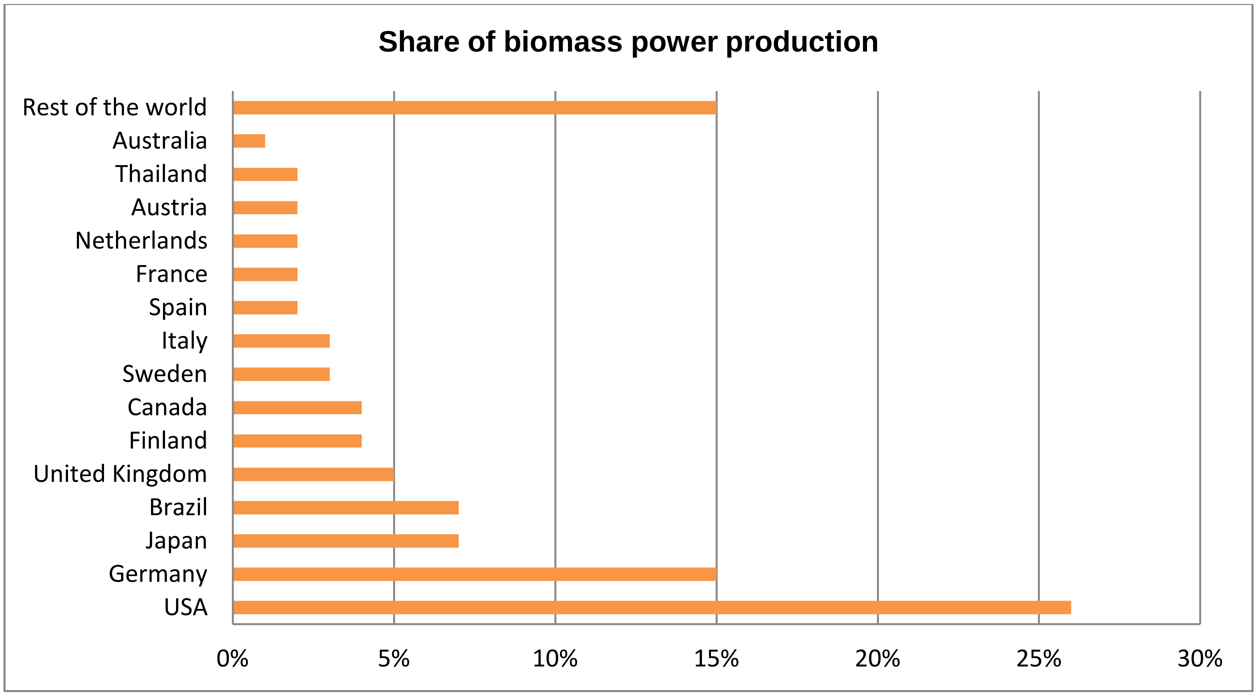


Figure 4 Global distribution of biomass energy use in 2008 (Source: Adapted from Evans, 2010)

The power generation capacity and total electricity production from different biomass feedstock in EU member states for existing as well as future expansion plans are presented in Figure 5 and Figure 6.

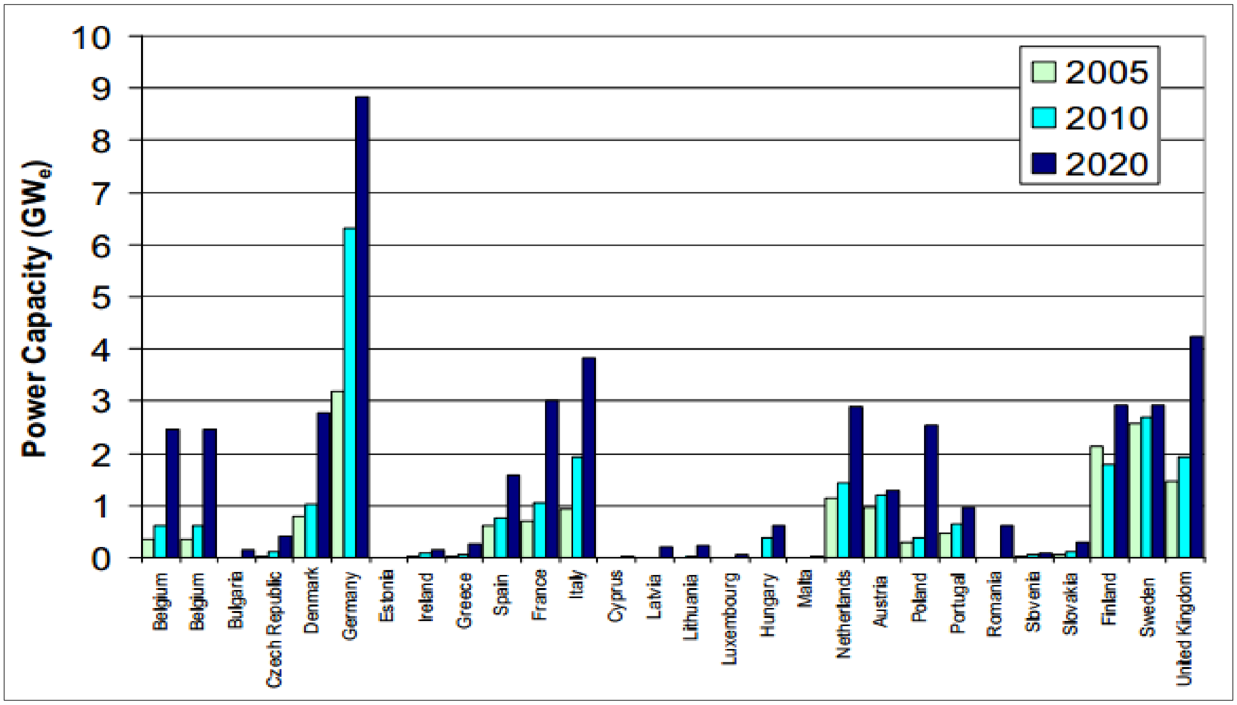


Figure 5 Biomass power production capacity (GW_e) in 2005, 2010 and 2020 in accordance with EU National Renewable Energy Action Plans (Source: EURELECTRIC, 2011)

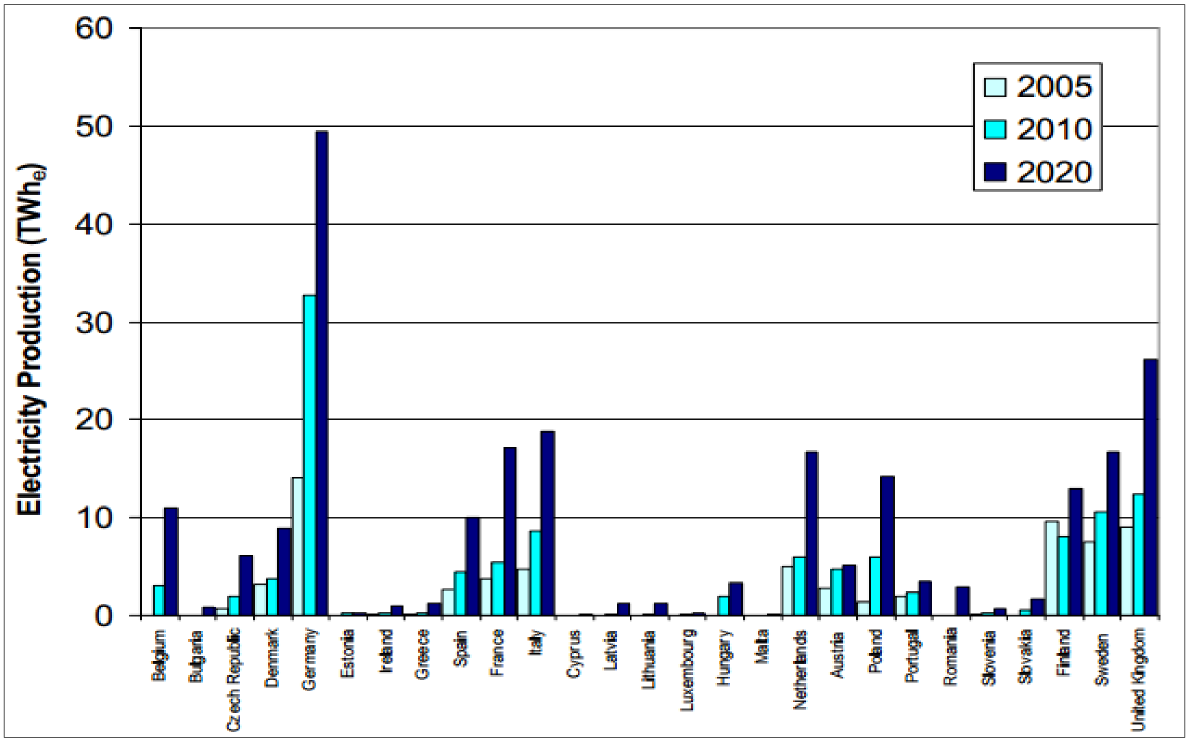


Figure 6 Biomass electricity production (TWh$_e$) in 2005, 2010 and 2020 in accordance with EU National Renewable Energy Action Plans (Source: EURELECTRIC, 2011)

In 2005, the total capacity of biomass power generation was 15.7 GW$_e$ including all the member states. With a production of 3 GW$_e$, Germany had the highest installed capacity, followed by Sweden (2.5 GW$_e$) and Finland (2 GW$_e$) (EURELECTRIC, 2011). Following the National Renewable Energy Action plans (NREAPs) by the member states, in 2010 there was ca. 23.6 GW$_e$ in place, and the ambition is to reach ca. 45 GW$_e$ of capacity by the end of 2020 to meet the renewable targets (EURELECTRIC, 2011).

As shown in Figure 5, there is significant variation in the national plans to increase biomass electricity production to reach the renewable targets by 2020. For example, Poland, expects to increase capacity six-fold between 2010 and 2020; Belgium plans to quadruple capacity; and many member states aim to double or triple capacity (e.g. UK, Italy, and France) (EURELECTRIC, 2011). This augmentation in capacity is broadly consistent with the growth in production, as shown in Figure 6.

However, many member states seemingly intend not only to expand capacity but also to increase the average load factor of biomass plants. This pattern is noticeable for states such as Sweden (small rise in capacity, production roughly doubled) and the Netherlands (capacity tripled, production quadrupled). But there is still some doubt whether the escalation in load factors is achievable or not (EURELECTRIC, 2011).

The countries which are actively involved in the gasification of various biomass feedstock for diverse applications including electricity production are mentioned in Table 3.

Table 3 Leading countries engaged in the gasification of different biomass feedstocks (Source: Kirkels, 2011)

Biomass	Wood	Peat	Black liquor	Municipal waste	Agricultural residue	Sludge	Rice husk
USA	USA	Finland	USA	USA	USA	USA	India
Japan	Japan	USA	Sweden	Japan	Greece	Japan	China
china			Finland		Turkey		Canada
					Spain		

2.3 Energy conversion routes from biomass

Biomass conversion is the process by which different biomass feedstocks are transformed into the form of energy that can be used for generating heat, electricity, and other products (IRENA, 2012). Converting the potential energy content of biomass into useful forms of energy is attainable through various technologies which are different in their efficiency range, level of development, investments, operation and maintenance costs, and labor requirements. Basically, the type of feedstock, their physical characteristics and chemical compositions influence the whole process of proper utilization of biomass. The operation of biomass based power plants for electricity production is somehow similar to conventional thermal power plants (EURELECTRIC, 2011). The main categories of biomass conversion processes are thermo-chemical and bio-chemical processes with varied technology options within each group (Zhang, 2010).

Generally, thermo-chemical processes are more efficient than bio-chemical processes as they require lower reaction time (a few seconds or minutes for thermo-chemical processes vs. several days, weeks or even longer for bio-chemical processes) and they have the ability to dismantle most of the organic compounds (Zhang, 2010). For example, lignin materials are typically considered to be non-fermentable and thus cannot be totally decomposed via bio-chemical approaches, while they are decomposable via thermo-chemical approaches (Zhang, 2010).

Thermo-chemical conversion processes include direct combustion, pyrolysis, gasification, and liquefaction. The three primary routes for bio-chemical conversion are digestion (anaerobic and aerobic), fermentation, and enzymatic or acid hydrolysis (Basu, 2010). The main conversion processes and their final products are illustrated in Figure 7 where it shows that the stored energy within biomass could be released directly as heat via combustion/co-firing or could be transformed into solid (e.g. charcoal), liquid (e.g. bio-oils) or gaseous fuels (e.g. synthetic gas) via pyrolysis or gasification with various utilization purposes (Zhang, 2010).

Bio-chemical technologies are mainly used for alcohol production through fermentation and methane-enriched gas production through anaerobic digestion. These primary products are usually consumed as transport fuels and occasionally in engines and turbines as fuel for electrical power generation (Akhtari, 2014; McKendry, 2002). The selection and design of biomass power plant is settled mainly by the characteristics of the fuel to be used, environmental regulations, the costs and performance of the equipments, the type of product (heat/electricity), and at what capacity this is required (EURELECTRIC, 2011).

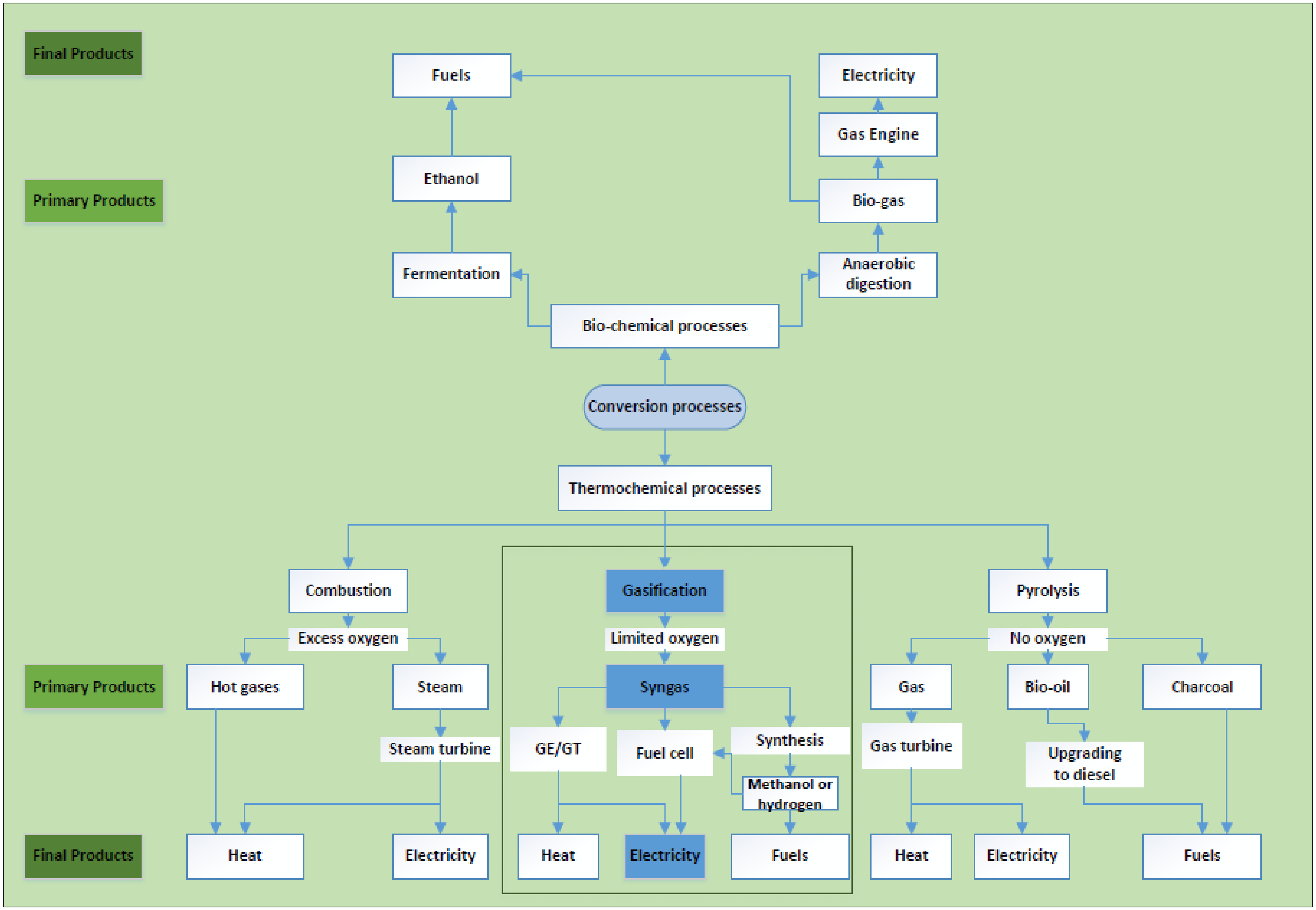


Figure 7 Biomass conversion processes and their end products (Source: Adapted from Akhtari, 2014)

Combustion involves high-temperature thermo-chemical conversion of biomass in excess air into CO_2 and steam at around 800-1000^{0}C (Shafie, 2012; Basu, 2010). Direct combustion means the complete oxidation of biomass in an aerobic environment (Evans, 2010). The chemical energy of the biomass is decomposed by this process and then converted into heat that can be used for both heating and electricity production purposes by the use of state-of-the-art technologies such as boilers, steam turbines etc. (McKendry, 2002). The most common combustors are pile burner, stoker grate, bubbling and circulating fluidized bed combustors, suspension burners etc. Additionally, biomass can be co-fired with coal in a coal-fired power plant. Direct co-firing is the process of adding a certain portion of biomass to the fuel mix in a coal-fired power plant. When the percentage of biomass is more than 10% then biomass and coal are burned separately in different boilers known as parallel co-firing (IRENA, 2012).

Gasification involves the partial combustion of the biomass converting it into a gaseous product (syngas) in an oxygen-deficient environment (Basu, 2010). Syngas consists primarily of carbon monoxide and hydrogen (Roos, 2010). It can be considered as the intermediate step between pyrolysis and combustion (Shafie, 2012). The common types are fixed bed, fluidized bed, and entrained flow gasifiers. The produced gas can be used with gas engines, micro-turbines, fuel cells or gas turbines (Basu, 2010). It is also possible to use the co-firing concept either directly i.e. biomass and coal are gasified together or indirectly i.e. separately gasifying coal and biomass for using in gas turbines (IRENA, 2012).

Pyrolysis takes place at a relatively lower temperature with no presence of oxygen (Basu, 2010). In a sense, pyrolysis is a subset of gasification system (Shafie, 2012). The products of the process are liquid bio-oil, alongside gaseous and solid products (charcoal). The pyrolysis oil can be used as a fuel for the production of electricity (IRENA, 2012). The pyrolysis can be divided into three subclasses: slow pyrolysis, fast pyrolysis and flash pyrolysis (Shafie, 2012). This technology is favorable for converting waste biomass into useful liquid fuels (Basu, 2010).

Anaerobic digestion is a process which takes place within any biological material that is decomposing and it is favored by warm, wet and unaired conditions (IRENA, 2012). The main products of this process are CH_4 and CO_2 and this is referred to as biogas (Basu, 2010). After cleaning up the biogas can be used in internal combustion engines (ICE), micro-turbines, gas turbines, fuel cells, stirling engines or it can be further upgraded to bio-methane for distribution through gas pipelines (IRENA, 2012).

Fermentation is the process where part of the biomass is converted into sugars using acid or enzymes. The sugar is then converted into ethanol or other chemicals with the presence of yeasts. The lignin part remains unchanged and is left either for combustion or thermo-chemical conversion into chemicals (Basu, 2010).

In short, the overall cost of biomass conversion process varies with the capacity of energy production, type of conversion technology used, and type of feedstock. This study focuses specifically on gasification based thermo-chemical processes where heat and electricity are considered as the main products of the process. But, as of now biomass is mostly converted into electricity by means of direct combustion though gasification technology has the capability to be utilized in large scales for producing electricity in rural areas of the developing countries.

The specific reviews about the current state of the major biomass conversion technologies are presented in Table 4 by compiling data from various sources. The key parameters on which the literature focuses on are electrical efficiency, scaling of the plant, technology-specific issues, and present development state. The production cost of electricity with each specific technology is also mentioned.

2.4 Main products of biomass conversions

There are three types of primary fuels that are produced from biomass using the conversion processes (Basu, 2010). These are as follows:

- Liquid: ethanol, biodiesel, methanol, vegetable oil, and pyrolysis oil
- Gaseous: biogas (CH_4, CO_2), producer gas (CO, H_2, CH_4, CO_2, H_2O), syngas (CO, H_2), substitute natural gas (CH_4)
- Solid: charcoal, torrefied biomass

From these fuels originate four major categories of product as follows (Basu, 2010):

- Electricity
- Heat energy
- Transportation fuels
- Chemicals (e.g. fertilizer, synthetic fiber etc.)

Heat and electricity are two basic forms of primary energy that are derived from combustion of biomass and this is a widely practiced commercial technology (Kaygusuz, 2009; Roos, 2010).

The product of biomass gasification are diverse in nature such as power, heat, combustible gas, chemical feedstock, hydrogen, bio-char, etc. (Roos, 2010).

The main product of biomass pyrolysis is a liquid fuel known as bio-oil. Power, heat, and combustible gas may also be produced using pyrolysis technology (Roos, 2010).

Biomass may support the substitution of petro-derived transport fuels (i.e. gasoline, diesel). Ethanol which is produced from sugarcane and corn using fermentation method is useable in gasoline (spark-ignition) engines; on the other hand biodiesel which is mainly derived from vegetable oils such as rape seed is useable in diesel (compression-ignition) engines (Basu, 2010; Roos, 2010).

Main products of anaerobic digestion which is a bio-chemical conversion method include biogas, and fertilizers (Roos, 2010; Basu, 2010).

Table 4 Overview on the efficiency, cost of electricity, capacity ranges, and development state of the main solid biomass and biogas conversion technologies for electricity production (Source: [a]Baxter, 2011; [b]Bauen, 2009; [c]Chum, 2011; [d]IEA, 2012a; [e]IRENA, 2013; [f]Fiorese, 2014; [g]Faaij, 2006)

Technology	Electrical Efficiency[a]	Cost of electricity (cUSD/kWh$_e$)	Scale of the plant[f]	General issues[f]	Development state[f]
Combustion + Steam Cycle	15–30%	7 – 9[b] 5 – 18[e] 10.4 – 21.7 (large)[d] 6.9 – 24.3 (medium)[d] 11.3 – 37.3 (small)[d]	Viable for large scale (30–100 MW$_e$) Recent development of small scale applications	Reliable technology Difficult biomass procurement for large scale	Commercial
Combustion + Stirling Engine	Around 30%	15 – 24[b]	Micro scale application (10–100 kW$_e$)	-	Demonstration
Combustion + ORC	16–20%	11 – 25[b]	Small scale (0.5–2 MW$_e$)	Few ORC plants operate on biomass Need to improve efficiency and reliability, and to reduce costs	Demonstration/ Early commercial
CHP Plants (Biomass Based) + Gas Engine[g]	Overall - 70–90% elec. - 15 – 30%[g]	7.5 – 13[b] 6.5 – 25[e]	Scale is limited by heat demand and its seasonal variation (0.1 – 1 MW$_e$)[g]	Need to find an economic application for waste heat	Commercial
Gasification + Gas Engine	22–35%	6.5 – 8[b] 10 – 14[c]	High efficiency also at small scale (0.01–10 MW$_e$)	Complex technology Reliability and efficiency must be proven	Demonstration/ Early commercial
Gasification + IGCC (BIG/CC)[g]	Up to 40 – 50%[g]	10.5 – 13.5[b]	High efficiency also at large scale (30 – 100 MW$_e$)[g]	Complex technology Reliability and efficiency must be proven	Demonstration
Direct Co-Firing	35–45% (at 10% biomass on energy base)	3 – 5.5[b] 2.9 – 5.3[c] 6.9 – 12.2[d] 3.5 – 12[e]	Medium to large-scale	Because of biomass varying characteristics, there are limits to the amount of biomass that can be used for co-firing Possible impacts on plant operation and lifetime	Commercial
Fast Pyrolysis	80% (conversion Efficiency of biomass in bio-oil)	7 – 15[c]	-	Bio-oil is cheaper to handle, store and transport High energy density	Basic and Applied R&D/ Demonstration
Anaerobic Digestion + Biogas in CHP	32–45%	16 – 22[b]	Decentralized farm-sized units (0.25–2.5 MW$_e$)	Feedstocks are manure, slurries and sewage Co-feeding agricultural residues and crops increases efficiency	Commercial

2.5 Significance of biomass gasification power generation

Production of electricity using biomass gasification is a prominent technology which supports efficient and clean utilization of residual woody biomass feedstock. This technology has several benefits such as renewability, environmental protection, sociopolitical advantages, etc. It has some distinguished characteristics compared to combustion and others which are as follows:

- Strong adaptability—it has the ability to handle many kinds of biomass feed materials such as straw, rice husk, sawdust, bagasse etc. making it a suitable technology for the widely distributed biomass resources in any agricultural country (Zhou, 2012).
- Greater flexibility—it is allowable to choose suitable subsequent electricity producing mechanism according to its scaling. Different secondary conversion technologies, such as gas engines, gas turbines, exhaust heat boilers and steam turbines, fuel cells can be integrated into its electricity generation process (Roos, 2010). Gas turbines, fuel cells and engines are more efficient electrical generation technologies compared to steam cycle (Roos, 2010). For these reasons gasification finds commercial acceptability even at a relatively small scale (Zhou, 2012).
- Enhanced environmental friendliness—gasification plants emit significantly lower quantities of major air pollutants like CO_2, SO_2, NO_x, and particulate matters (Basu, 2010; Ruiz, 2013). Gasification technology helps to lower the emission of NO_x because all the gasification processes take place at relatively low temperatures which inhibit the formation of NO_x (Zhou, 2012). A BIGCC plant produces lower amount of CO_2 per MWh_e than a combustion-based steam power plant (Basu, 2010). Table 5 shows a comparison about the emissions of different pollutants from three electricity generation technologies.
- Polygeneration—this is a unique feature of a gasifier plant. It can deliver steam for process, electricity for grid, and gas for synthesis, i.e. a good product mix (Roos, 2010). Also for a high-sulfur containing fuel a gasifier plant produces elemental sulfur as a by-product; for high-ash containing fuel, it provides slag or fly ash which could be useful in cement manufacturing plant (Basu, 2010).
- Decentralized electricity production—rapid economic and social development underpinned the strong growth in electricity demand. Although the power production is increasing continuously, still in many developing countries there are acute power shortages. Biomass gasification based power generation can be a good alternative to solve scarcity of electricity in rural areas where grid connection is still absent (Zhou, 2012; Buragohain, 2010). Biomass is a locally grown resource. For a good economic success biomass based power plant should be located in a site where feedstocks are available within a certain distance. A biomass based power plant can initiate the establishment of associated businesses, such as biomass yielding, collecting and storing, and transporting to plant site, etc. Thus it can also create plenty of job opportunities as well as boost the local economy. Technologically compared with a combustion system that comprised of a boiler, a steam engine, and a condenser a gasification system comprises a gasifier and a gas engine; which is more reasonable for small scale power generation (Basu, 2010).
- Energy safety—an important aspect of biomass based energy, fuel or a chemical is that they considerably reduce the reliance on imported fossil fuels for countries (Kirkels,

2011). The unstable global political situation implies that supply and price of fossil fuels can change drastically within a short period of time. On the other hand locally grown biomass feedstocks are relatively free from such contingency (Basu, 2010).

Table 5 Comparison of emissions from three different electricity generation technologies (Source: Basu, 2010)

Emission	Pulverized-Coal Combustion	Gasification	Combined Natural-Gas Combustion
CO_2 (kg/1000 MWh_e)	0.77	0.68	0.36
Water use (l/1000 MWh_e)	4.62	2.84	2.16
SO_2 (kg/MWh_e)	0.68	0.045	0
NO_x (kg/MWh_e)	0.61	0.082	0.09
Total solids (kg/100 MWh_e)	0.98	0.34	0

For these reasons, mentioned above, it is considered useful to promote biomass gasification technology for small, medium and large scale power generations in greater extent (Zhou, 2012).

2.6 The process of biomass gasification

Gasification is a thermo-chemical partial oxidation process in which carbonaceous substances such as biomass, coal, and plastics are converted into gas in the presence of a gasifying agent like air, steam, oxygen, CO_2 or a mixture of these (Basu, 2010). The gas generated by the process is commonly termed as syngas (synthesis gas) (Roos, 2010). This syngas mainly consists of H_2, CO, CO_2, N_2, small particles of char (solid carbonaceous residue), ashes, tars, and oils (Basu, 2010). Gasification takes place typically at around 800-900^{0}C at a pressure range starting from atmospheric state up to 33 bar (Ruiz, 2013; Difs, 2010; Evans, 2010). The composition of syngas is altered by gasification conditions, such as temperature, equivalence ratio, pressure, etc. Usually, it is difficult to provide a solid theory for describing the whole process of biomass gasification due to the variety of raw materials available. But the pyrolysis process followed by volatilization of the remaining carbon is predominant in all incidents of gasification (Pereira, 2012). According to Basu (2010), the different stages of gasification overlap and there is no clear limit between them. The main steps of the thermo-chemical gasification process are shown in Figure 8.

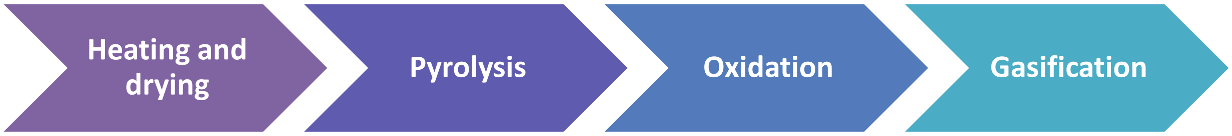


Figure 8 Gasification process steps (Source: Adapted from Ruiz, 2013)

First step: heating and drying of solids—biomass collected from different sources may contain high moisture contents. The typical moisture content of freshly cut wood ranges from 30% to 60%, and may exceed 90% in some samples of biomass (Ruiz, 2013). Drying is an energy intensive process which may downturn the overall energy efficiency of the process. However, in case of gasification, waste heat can be utilized to reduce the moisture content of the biomass which results in an increase to the overall efficiency of the process (Kumar, 2009). Perforated bin dryers, band conveyor dryers and rotary cascade dryers have been used to dry biomass (Cummer, 2002). Depending on the moisture level of biomass, drying processes are selected, preferably prior to entry in the gasifier. For gasification, moisture content should be between 10% and 15% (Basu, 2010). In the case of generating combined heat and power (CHP), biomass moisture content should be as low as possible to increase the overall efficiency and decrease the net cost of electricity. In case of raw biomass with lower moisture content (e.g. less than 10%) drying stage may not be required (Brammer, 2002).

Second step: pyrolysis—this process occurs in between 150 to 400^0C and results in the formation of a solid carbonaceous material known as “char” along with other gases (Ruiz, 2013). The main components of this gaseous phase are H_2O, CO_2, H_2, hydrocarbons and smaller quantities of other compounds (organic acids) (Ruiz, 2013). The hydrocarbon fraction comprises methane, and organic compounds known as tars, which are a problem above a certain concentration. The breakdown of this hydrocarbon fraction may be influenced by various parameters such as particle size, temperature, pressure, heating time and residence time (Ruiz, 2013; Basu, 2010; Kaygusuz, 2009).

Following step: oxidation—this is the partial combustion of some gases, steam and char by a gasification agent, usually air. Part of the compound is then converted to CO, CO_2 and H_2O. The required energy for the reduction and pyrolysis reactions is generated at this stage (Ruiz, 2013; Basu, 2010).

Final step: gasification—in this stage the gasification or reduction of the char produced during pyrolysis take place. The char is converted mainly to CO, CH_4 and H_2 (Basu, 2010). Biomass char is usually more porous and reactive than char produced from coke. The pores in biomass char are larger than those from fossil char. The differences are considerable enough for the gasification reactions to be distinctive from those of coal, lignite or peat (Ruiz, 2013).

The overall reaction in an air and/or steam gasifier is shown below, which then proceeds with multiple reactions and pathways (Kumar, 2009). In short, in the presence of an oxidizing agent at high temperature, the large polymeric molecules of biomass decompose into lighter molecules and eventually to permanent gases (CO, H_2, CH_4 and lighter hydrocarbons), ash, char, tar, and minor contaminants where char and tar results due to incomplete conversion of biomass (Kumar, 2009).

$$\mathbf{CH_xO_y\ (biomass) + O_2\ (21\%\ of\ air) + H_2O\ (steam) = CH_4 + CO + CO_2 + H_2 + H_2O\ (unreacted\ steam) + C\ (char) + tar}$$

However, the gasification of biomass char involves several reactions between the char and the gasifying agents which produce CO and H_2 (Ruiz, 2013). The main reactions that take place in the gasification process are shown in Table 6. The first two reactions (R1 and R2) are endothermic and the heat required to cause them is supplied mainly by the oxidation reaction (R5), which is highly exothermic (Ruiz, 2013; Basu, 2010). The final outcome of these whole processes is a gas made up mainly of CO, H_2, N_2, CO_2, H_2O and hydrocarbons. Very small quantities of NH_3, H_2S and tars are also present in the gas (Ruiz, 2013). After cleaning, this gas can be burned to produce mechanical or electrical energy with no waste by-products, and also maintaining the environmental regulations on pollutant gas emissions (Ruiz, 2013).

Table 6 Typical gasification reactions at 25^{0}C (Source: Compiled from Basu, 2010; Ruiz, 2013; Zhang, 2010)

Reaction Type	Reaction
Carbon Reactions	
R1 (*Boudouard*)	$C + CO_2 \leftrightarrow 2CO + 172$ kJ/mol
R2 (water-gas or steam)	$C + H_2O \leftrightarrow CO + H_2 + 131$ kJ/mol
R3 (hydrogasification)	$C + 2H_2 \leftrightarrow CH_4 – 74.8$ kJ/mol
R4	$C + 1/2\ O_2 \rightarrow CO – 111$ kJ/mol
Oxidation Reactions	
R5	$C + O_2 \rightarrow CO_2 – 394$ kJ/mol
R6	$CO + 1/2\ O_2 \rightarrow CO_2 – 284$ kJ/mol
R7	$CH_4 + 2O_2 \leftrightarrow CO_2 + 2H_2O – 803$ kJ/mol
R8	$H_2 + 1/2\ O_2 \rightarrow H_2O – 242$ kJ/mol
Water-Gas Shift Reaction	
R9	$CO + H_2O \leftrightarrow CO_2 + H_2 – 41.2$ kJ/mol
Methanation Reactions	
R10	$2CO + 2H_2 \rightarrow CH_4 + CO_2 – 247$ kJ/mol
R11	$CO + 3H_2 \leftrightarrow CH_4 + H_2O – 206$ kJ/mol
R14	$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O – 165$ kJ/mol
Steam-Reforming Reactions	
R12	$CH_4 + H_2O \leftrightarrow CO + 3H_2 + 206$ kJ/mol
R13	$CH_4 + 1/2\ O_2 \rightarrow CO + 2H_2 – 36$ kJ/mol

The gasification of char in carbon dioxide is commonly known as the *Boudouard reaction* which is reaction R1 in Table 6 (Kumar, 2009; Basu, 2010).

The gasification of char in steam, known as the water-gas reaction, is considered as the most significant gasification reaction which is reaction R2 in Table 6 (Kumar, 2009; Basu, 2010).

Hydrogasification reaction involves the gasification of char in presence of hydrogen, which eventually leads to the formation of methane (Kumar, 2009). This is reaction R3 in Table 6. This reaction is much slower and it is only significant when the production of synthetic natural gas (SNG) is desired (Basu, 2010).

The reactions R4, R5 and R8 are the most common oxidation reactions that occur in the presence of oxygen referred to Table 6 (Kumar, 2009). Here the reactions R4 and R5 are exothermic, they generate enough heat for drying the feedstock, to break up the chemical bonds (pyrolysis of biomass), and to maintain a high temperature for driving the gasification reactions.

Among these reactions, reaction R5 gives the highest amount of heat (394 kJ) per kmol of consumed carbon (Basu, 2010). In contrast, the heat generation capacity of reaction R4 is only ca. 65% of that of reaction R5. The speed of R4 is comparatively slow (Zhang, 2010).

In addition, the shift reaction is an important gas-phase reaction. The water-gas shift reaction R9 has great influence since it plays a significant role for hydrogen generation in the gasification process at the expense of carbon monoxide (Kumar, 2009). This reaction mainly occurs between steam and carbon monoxide, and it is much different from the water-gas reaction (R2) (Basu, 2010).

Reaction R11 referred to Table 6 is the methanation reaction. It proceeds slowly at low-temperatures and without help of any catalysts (Basu, 2010). Both reactions R9 and R11 take place in either direction depending on the specific temperature, pressure, and the reactant concentrations in the system (Zhang, 2010).

Syngas can also be produced from natural gas (>80% CH4), using a steam-methane-reforming reaction, compared to only solid carbonaceous fuel. The reactions R12 and R13 are examples of steam reforming reaction. The hydrogen produced during the process can be used as fuel in fuel cells or in the production of chemical feedstock like methanol and ammonia (Basu, 2010).

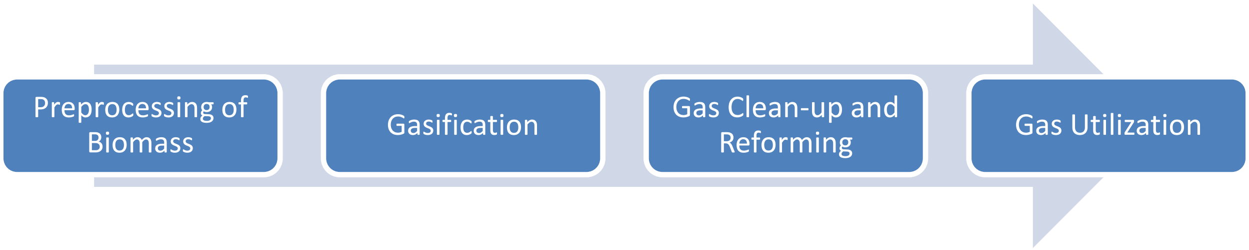
Lastly, after analyzing all these reactions it can be seen that the syngas is a mixture that is mainly composed of CO, H_2, CO_2, CH_4, and H_2O vapor (Rezaiyan, 2005; McKendry, 2002).

Gasifying Mediums—gasifying agents react with solid carbon and heavier hydrocarbons to transform them into low-molecular-weight gases like CO and H_2. The main gasifying agents used for gasification are—(1) Oxygen (2) Steam and (3) Air (Basu, 2010). The choice of gasifying agent affects the heating value of the product gas. From Table 7, it can be seen that oxygen gasification has the highest heating value followed by steam and air gasification (Basu, 2010). The selection of gasifying agent entirely depends on the requirement of the product gas quality for different downstream applications. Carbon dioxide can also act as a gasifying agent to react with carbon to produce carbon monoxide; however, the reaction is rather slow (Asadullah, 2014).

Table 7 Heating values for product gas based on gasifying medium (Source: Basu, 2010)

Medium	Heating Value (MJ/Nm^3)
Air	4—7
Steam	10—18
Oxygen	12—28

Finally, the main steps involved in the gasification process can be categorized as upstream processing, gasification and downstream processing as shown in Figure 9 (Kumar, 2009).



Size reduction, Drying, Preparation of gasifying agents	Heating, Chemical Reactions, Catalysis	Cleaning of tar from syngas, Reforming of the syngas, Catalysis	Gas turbine, Gas engine, Fuel cell, Combined heat and power
Upstream processing	**Gasification**	**Downstream processing**	

Figure 9 Processes involved in biomass gasification (Source: Adapted from Kumar, 2009)

2.7 Technologies used for biomass gasification

Gasifiers are the reactors in which gasification reaction take place. A gasifier is the major component of a biomass gasification plant. Inside the gasifier the biomass fuel and the gasifying agent are mixed to a lesser or greater extent, in some cases together with other inert materials, catalysts or additives (Ruiz, 2013). The way in which the reagents, biomass and gasifying agent come into contact with the gasifier is important and forms the basis for the fundamental classification of gasifiers (Balat, 2009). Based on the types of reactions, a typical air-blown gasifier can be divided into four process zones – the drying zone, where water present in biomass is evaporated; the pyrolysis zone, in which biomass is pyrolyzed into medium-energy calorific volatile gases, liquid, and char; the combustion zone, a region where combustion reactions take place with limited amounts of air or oxygen provided; and the reduction zone, in which CO and H_2 are produced (Zhang, 2010). Various types of gasifiers have been developed so far, such as fixed-bed gasifiers, fluidized bed gasifiers, and entrained flow gasifiers. These are explained in details in the following sections.

There are many possible configurations for gasification, and gasifiers can be classified with respect to four distinct characteristics (IRENA, 2012). These are as follows:

- **Oxidation agent:** this can be air, oxygen, steam or a mixture of these gases.
- **Heat for the process:** this can be either direct (i.e. within the reactor vessel by the combustion process) or indirect (i.e. provided from an external source to the reactor).
- **The pressure level:** gasification can take place at atmospheric pressure or at higher pressures.
- **Reactor type:** based on the gas-solid contacting mode these are fixed bed, fluidized bed or entrained flow. Each of these is further subdivided into specific types as shown in Figure 10.

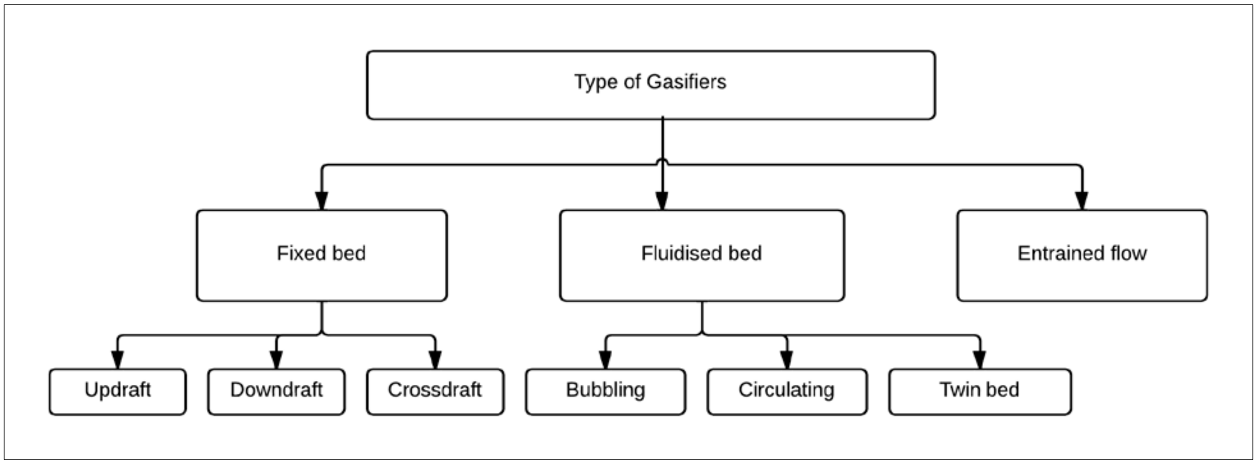


Figure 10 Classification of gasifiers (Source: Basu, 2010)

One of the key characteristic of gasifiers which is needed to be considered is the size range to which they are suited. One particular gasifier type may not be well suited for the full range of gasifier capacities. There is an appropriate range of application for each of these technologies (Basu, 2010). For instance, the fixed bed gasifiers (updraft and downdraft) are used for small scale applications with typical range 10 kW_{th}-10 MW_{th} (Basu, 2010; IRENA, 2012). The fluidized bed gasifiers are suitable for medium up to large scale applications with different configurations. Their typical scales are ranges from 5 MW_{th} up to 300 MW_{th} (Basu, 2010; IRENA, 2012). Entrained flow reactors are used widely for large-capacity plants (>100 MW_{th}) (Basu, 2010; IRENA, 2012). Figure 11 shows the overlapped range of application for different types of gasifiers from where it can be depicted that the downdraft gasifiers are used for small scale applications and entrained flow gasifiers are used for the largest scale applications.

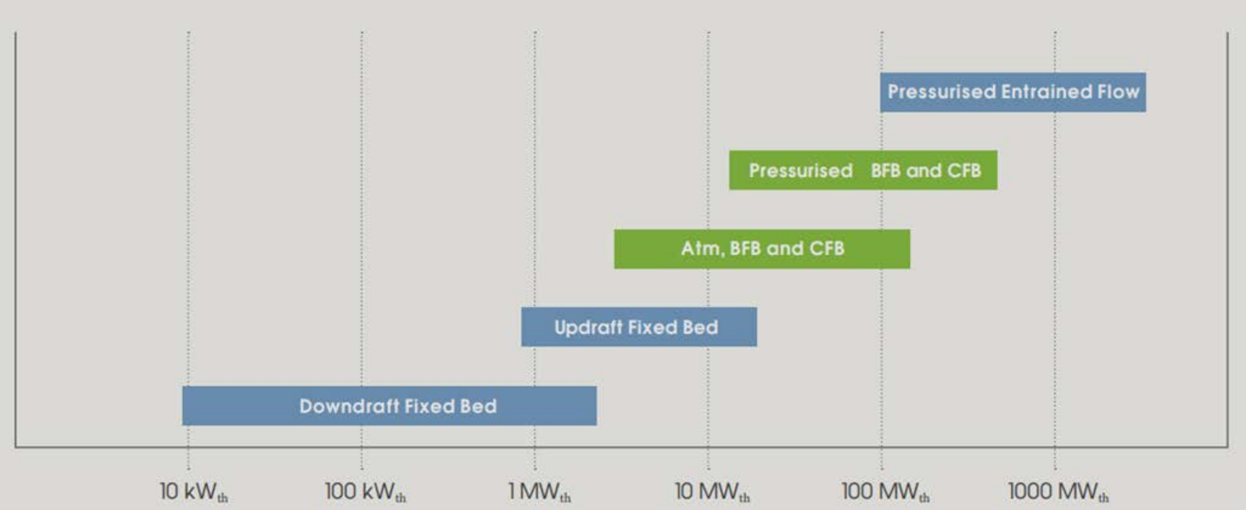


Figure 11 Gasifier type by scale range considering thermal input (Source: IRENA, 2012)

2.7.1 Fixed bed gasifiers

Fixed bed gasifiers generally have a grate to support the gasifying biomass and maintain a stationary reaction bed. They are comparatively easy to design and operate and they have fewer problems with erosion of the reactor body. This type of reactors can be built inexpensively in small sizes which is one of their major advantages. This is also the reason why large number of small-scale fixed bed gasifiers is in operation in many countries (Basu, 2010; IRENA, 2012). There are three main types of fixed bed gasifiers: updraft (or counter-current type), downdraft (or co-current type), and crossdraft which are discussed in following section.

2.7.1.1 Updraft gasifiers

An updraft gasifier i.e. counter-current is one of the simplest among all types. It has high thermal efficiency, is easy to control, and more tolerant of fuel switching compared to downdraft gasifiers (Roos, 2010).

In an updraft gasifier the biomass is fed in from the top of the reactor, and the gas generated also leaves the reactor via the top (Buragohain, 2010). The gasifying agent (air, oxygen, steam or a mixture of them) enters the gasifier at the bottom through a grate (Ruiz, 2013). It then travels upward through the bed of descending biomass or ash in the gasifier chamber. Here the feed and gasifying agent are in countercurrent mode (Basu, 2010).

The lower part of the gasifier is the combustion zone where the char formed due to drying and devolatilization of biomass is combusted and results in a temperature about 1000 K (Buragohain, 2010). Entering from the bottom of the gasifier, the gasifying agent comes into contact with the hot ash and non converted char falling from above. The ash drops through the grate, which is sometimes made moving to enhance ash discharge.

The area above the gasification area is where the pyrolysis of the biomass takes place. The residual heat in the updraft of hot air is transferred to the descending biomass, which is then heated and pyrolyzed (Ruiz, 2013). During the pyrolysis process the biomass is converted into non-condensable gases, condensable gases, char, and tar. Some of the tar leaves with the outgoing gases and rest remains inside. This is a major drawback for updraft gasifiers (Buragohain, 2010). Both types of gas rise and the char falls downwards with the other solids.

At the top, the biomass is dried by the heat transferred to it from the gas updraft. This gas is a mixture of products from both gasification and pyrolysis processes (Basu, 2010; Buragohain, 2010; Ruiz, 2013). The schematic representation of a simple updraft gasifier reactor is shown in Figure 12.

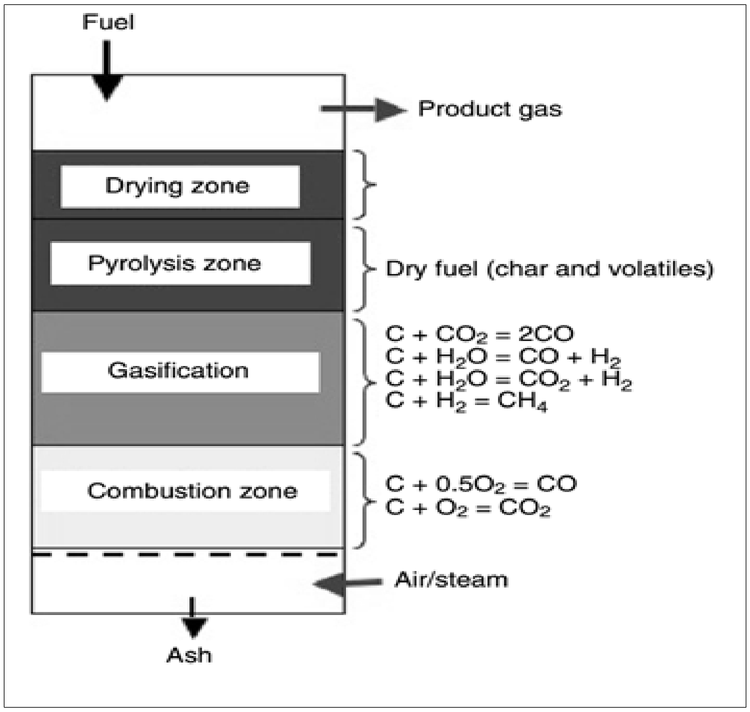


Figure 12 Schematic of an updraft gasifier (Source: Basu, 2010)

2.7.1.2 Downdraft gasifiers

A downdraft gasifier is a co-current reactor where the biomass is fed in from the top and drops downwards, while air is injected from one side at a certain height below the top and blends with the products of the pyrolysis. After that both gases and the solids (char and ash) move down in parallel streams through the reactor (Roos, 2010; Ruiz, 2013).

Part of the gas generated during pyrolysis may be burned in the gasification area. Thus the heat energy needed for drying, pyrolysis and gasification is provided by the combustion of pyrolytic gas. This is known as “pyrolytic flame” (Basu, 2010). The product gas of pyrolysis and combustion flows downward. The gas is then passed through a bed of hot ash, where gasification takes place afterwards. Due to the arrangement of the exit of the producer gas close to the combustion zone of the gasifier with maximum temperature, the tar formed during devolatilization of biomass gets thermally cracked to some extent (Buragohain, 2010).

This makes sure that the syngas produced contains less amount of tar, and that is why a downdraft gasifier, compared with all other types, has the lowest tar production rate which is considered as a big advantage of this technology because low tar content gas is always preferred for firing the gas engines and turbines (Basu, 2010). But on the other hand the gas has less calorific value because of the pyrolytic gases that are burned in order to provide the energy required for endothermic reactions (Basu, 2010; Ruiz, 2013). In Figure 13, the schematic of a downdraft gasifier is shown.

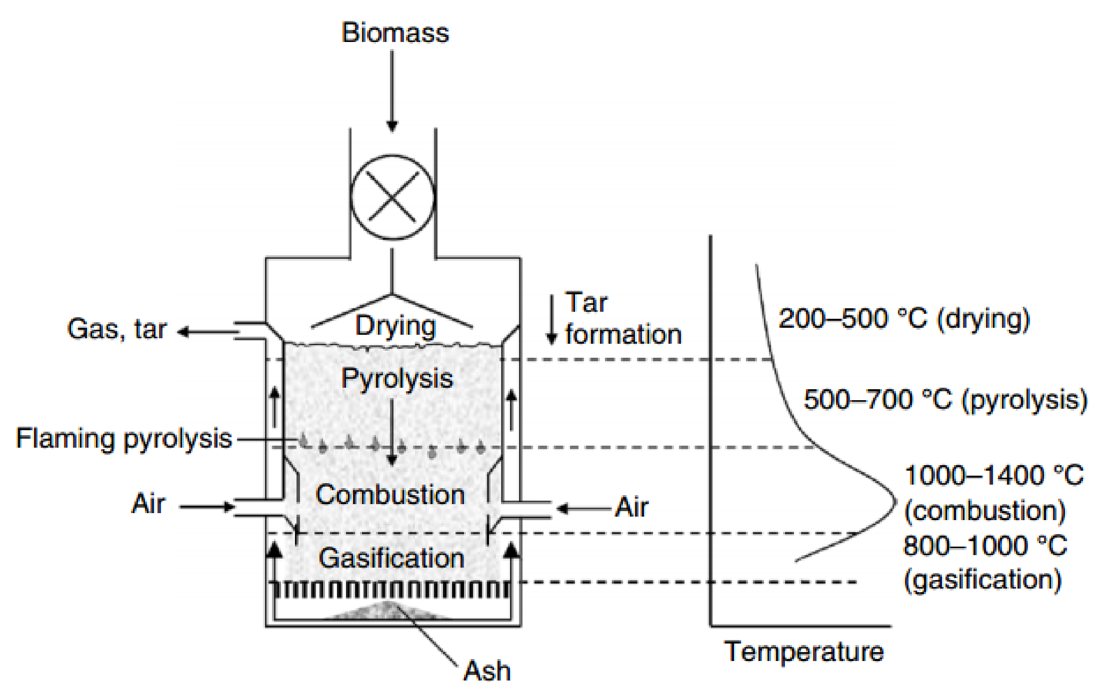


Figure 13 Schematic of a downdraft gasifier (Source: Basu, 2010)

2.7.1.3 Crossdraft gasifiers

A crossdraft gasifier is a co-current moving-bed reactor where the biomass is entered from the top and the air is injected through a nozzle from the side of the gasifier (Basu, 2010). The biomass travels downward as it gets dried, devolatilized, pyrolyzed and finally gasified. The exit for the gas is relatively at the same level as that of entrance (Buragohain, 2010).

The combustion and gasification zone is located near to entrance of the air while the devolatilization and pyrolysis zones are at a higher level than the entrance and exit of the gas (Zhang, 2013). Figure 14 shows schematically the cross-draft gasifier. The produced gas leaves the gasifier at almost same temperature as gasification (i.e. 800—900^{o}C) (Buragohain, 2010). Thus, the heat loss from the gasifier is elevated which in turns reduces its thermal efficiency. Another notable point is that the overall residence time of the produced gas in the high temperature zone is short (as the gas enters and exits from opposite ends), and as a result, tar cracking is constrained. Due to this significant amount of tar is present in the outgoing gas (Buragohain, 2010).

Crossdraft gasifiers can be very light and small (<10 kW_e) (Basu, 2010). This gasifier is less suitable for high-ash or high-tar biomass fuels, but it can handle high-moisture fuels if the upper part is kept open so that the moisture can escape easily. It works better with charcoal or pyrolyzed fuels (Basu, 2010).

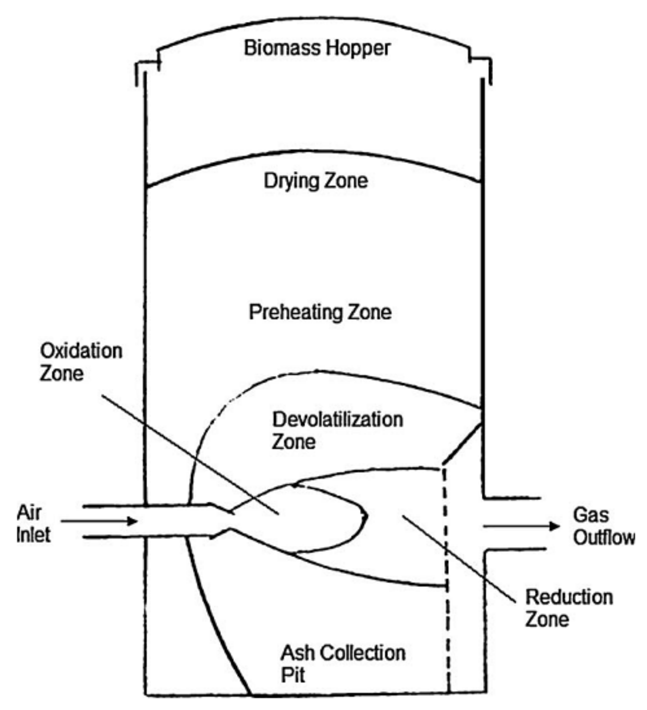


Figure 14 Schematic of a crossdraft gasifier (Source: Buragohain, 2010)

2.7.1.4 Overview on fixed bed biomass gasification

Some important points about fixed bed gasification are listed below:

Typical composition of the produced gas from fixed bed gasifiers is: 40-50% N_2, 15-20% H_2, 10-15% CO, 10-15% CO_2 and 3-5% CH_4 (Tijmensen, 2002). The net calorific value of the gas is in the range of 4-6 MJ/Nm^3 (Buragohain, 2010). Nitrogen in the producer gas contributes considerably to the volume of the producer gas, which increases the size of the downstream equipment (Tijmensen, 2002).

Typically, the moisture content of the biomass should be in the range of 10-15% for fixed bed gasification. Thus, considerable pre-drying of biomass is essential. Many commercial fixed bed downdraft gasifiers have the facility of using waste heat from engine exhaust for pre-drying of the biomass (Buragohain, 2010).

The main products of the devolatilization process are volatiles and char. Volatiles leave with outgoing gas, while the char undergoes combustion. This char can be gasified further to improve the gas yield from the process. Typical yield of char varies from 20 to 40% (w/w) of dry biomass (Buragohain, 2010).

Updraft gasifiers are suitable for high ash (up to 25%), high moisture (up to 60%) containing biomass fuels (Basu, 2010). Tar production is very high (30-150 g/Nm^3) in an updraft gasifier which makes it incompatible for high-volatility fuels. Due to its counter-current mechanism it can utilize combustion heat very effectively and have high cold-gas efficiency (Basu, 2010).

Downdraft gasifiers work well in combination with internal combustion engines e.g. gas engines. Lower tar content (0.015-3 g/Nm^3) in the product gas is an important reason for their use with gas engines. It requires shorter time (20-30 minutes) to ignite and bring the plant until working temperature compared to the time needed by an updraft gasifier (Basu, 2010).

Crossdraft gasifiers are generally used in small-scale biomass plants. It has relatively small reaction zone with low thermal capacity which allows a faster response time than that of other fixed bed reactors. It has startup time (5-10 minutes) which is much shorter than downdraft and updraft plants. It has low tar production (0.01-0.1 g/Nm^3) and requires simple gas-cleaning system (Basu, 2010).

2.7.2 Fluidized bed gasifiers

Fluidized bed technologies were first commercialized for coal gasification. The first commercial fluidized bed process, Winkler gasifier, went into operation in Germany in 1941. After that, these have been extensively implemented by the petroleum refineries and petrochemical industries (Buragohain, 2010). In recent years, fluidized bed biomass gasification has found acceptance for energy generation purposes (Roos, 2010). The distinct merits of these gasifiers over fixed bed biomass gasifiers are uniform temperature distribution in the reactor due to excellent gas-solid mixing, high carbon conversion with low tar production and flexibility in terms of fuel type, feed rate, particle size, and moisture content. Due to these excellent features, scale-up and operation of the fluidized bed gasifiers for electricity generation in medium to large scale is highly recommended (Buragohain, 2010).

There are two main types of fluidized bed gasification systems: bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) which can be either atmospheric or pressurized (IRENA, 2012). The design and operational features of these gasifiers are shortly described below.

2.7.2.1 Bubbling fluidized bed gasifiers

In this kind of gasifiers the bed material which could be a mixture of inert particles such as sand along with finely ground biomass stays on a distributor plate (either perforated or porous type) through which the fluidizing medium, i.e. air is delivered at a velocity about five times that of minimum fluidization velocity (Buragohain, 2010). Typical temperature in the bed is about 700-900^{0}C (Zhang, 2013; Basu, 2010).

The feed, which is finely grained biomass, is inserted just above the distributor plate. The biomass first experiences pyrolysis in the hot bed above distributor to yield char and gaseous products due to devolatilization. The char particles are then lifted along with fluidizing air and go through gasification in relatively upper part of the bed. Due to contact with high temperature bed, the tar compounds with high molecular weight previously formed are cracked; and the net amount of tar content in the producer gas is reduced in the range of 1-3 g/Nm^3 (Buragohain, 2010). Figure 15 shows an arrangement of a bubbling fluidized bed gasifier. These gasifiers are particularly suitable for medium-scale plants of capacity less than 25 MW$_{th}$ (Basu, 2010). Depending on the operating conditions these gasifiers can be categorized as low-temperature, high temperature, atmospheric pressure, or elevated pressure types (Basu, 2010).

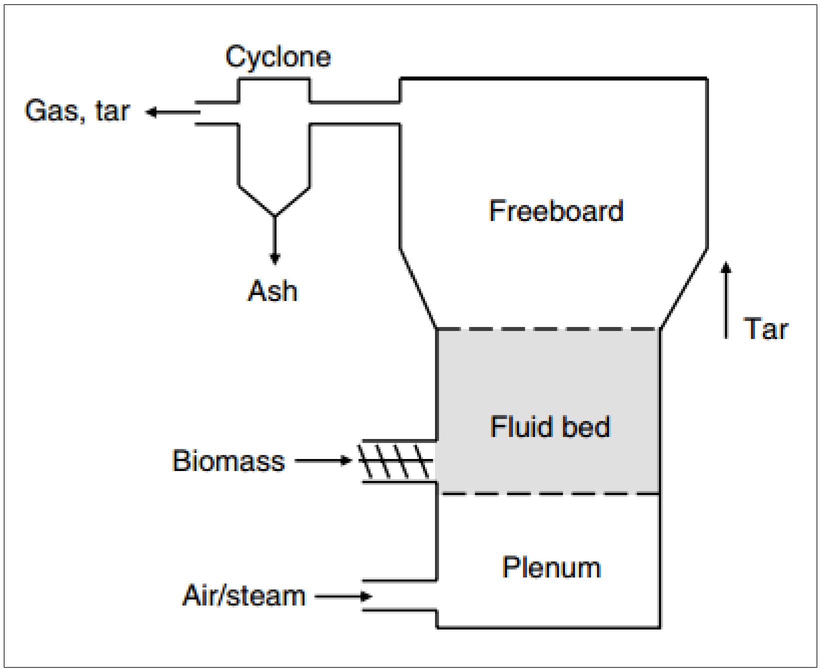


Figure 15 Schematic of a bubbling fluidized bed gasifier (Source: Basu, 2010)

2.7.2.2 Circulating fluidized bed gasifiers

This is an extension of the concept of bubbling bed fluidization. In this case the velocity of the fluidizing air is much higher than the terminal settling velocity of the bed material. Thus, the entire bed material (biomass and inert material such as sand) is raised by the fluidizing air (Buragohain, 2010). The product of the gasifier is a relatively lean mixture of solids and gases. This product is passed through a cyclone separator where solids get separated from the gas and are returned to the bed through a downward pipe (Basu, 2010).

Depending on the solids concentration and size distribution either single stage or multi-stage cyclones are selected. Circulation of the biomass particles is carried out till the particles are reduced in size due to combustion and gasification. An advantage of CFB gasifiers is that it allows operation at elevated pressures (Buragohain, 2010). Based on scale of operation, the cyclone separators for capture and recycle of solid particles could be placed either internally or externally. In the past two decades significant experimental and theoretical research has taken place in design, development and scale-up of fluidized bed gasifiers especially CFB (Yin, 2002).

CFB reactors require higher investments than that of BFB reactors due to increased complexity and size. However, they are more suitable for large scale and BIGCC plants as they work well with pressurized gas (Kirkels, 2011). Many commercial gasifiers of this type have been installed in different countries with different scale ranges (Basu, 2010). Figure 16 shows a schematic of a CFB gasifier developed by Foster Wheeler.

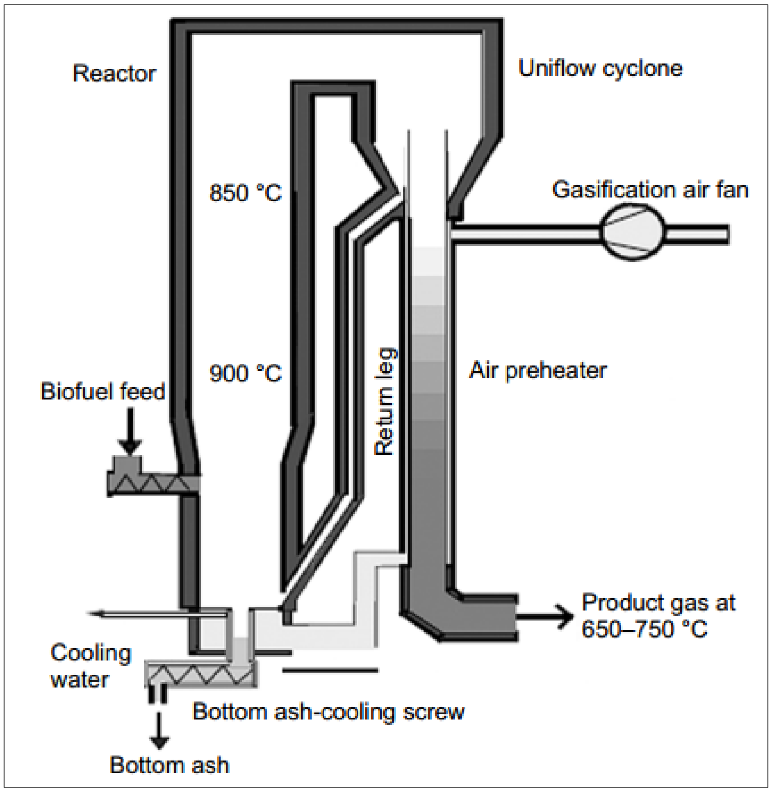


Figure 16 Schematic of a circulating fluidized bed gasifier (Source: Basu, 2010)

2.7.2.3 Twin fluidized bed gasifiers

These reactors are useful to produce gas with a higher calorific value than can be obtained with a single gasifier. They comprise of two reactors (Ruiz, 2013):

- The first reactor acts as a pyrolysing reactor, heated with sand or a hot inert material from the second reactor
- The second reactor obtains its heat by burning char from the first reactor

Figure 17 shows a schematic of a twin fluidized bed gasifier with char combustion mechanism. This particular system is comprised of a BFB gasifier and a CFB combustor. Here, pyrolysis and gasification take place inside the BFB which is fluidized by superheated steam. Tar and gas produced during the pyrolysis process are combusted in the riser's combustion zone. Heat generated by combustion process lifts the temperature of the inert bed material at 900^0C (Basu, 2010). This material escapes the riser and then captured by the cyclone at the riser exit. The collected solids fall into a pipe and then circulated back into the bubbling fluidized bed reactor to supply heat for its endothermic reactions. The char is gasified inside the BFB gasifier in the presence of steam, producing the product gas. This system reduces the problem of tar by burning it in the combustor zone. With this step a product gas relatively free of tar contents can be obtained (Basu, 2010).

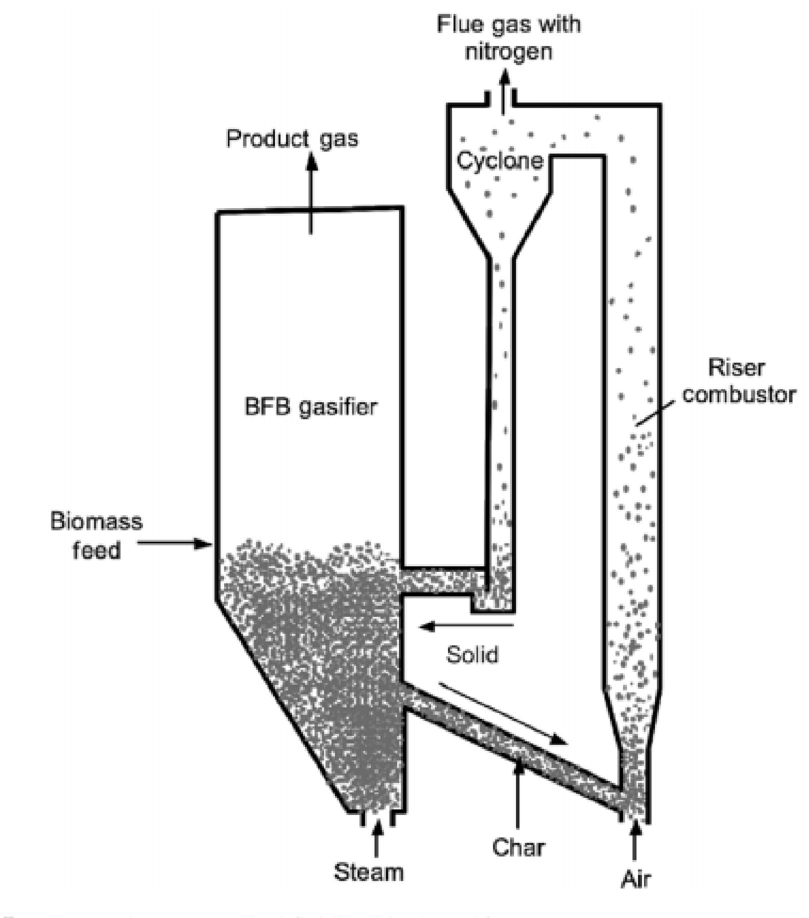


Figure 17 Schematic of a twin fluidized bed gasifier technology (Source: Basu, 2010)

2.7.2.4 Important aspects of fluidized bed gasifiers

Some important issues related to fluidized bed gasifiers are listed below:

Fluidized bed reactors cannot manage full conversion of char due to the continuous mixing of solids. The high degree of mixing of solids help to maintain a homogeneous temperature, but the close mixture of gasified and partially gasified particles implies that any solid that leaves the bed contains partially gasified char. The particles of char present in the fluidized bed can cause losses in the gasifier (Ruiz, 2013).

Fluidized bed gasifiers typically operate at temperatures of 800-1000^{0}C to prevent ash from building up. This is admissible for fuels such as biomass, municipal solid waste (MSW), refuse derived fuels (RDFs) and lignite. These reactors typically have no issues in processing fuels with high ash contents. These gasifiers accept a wide range of particle size (Ruiz, 2013).

Another advantage of this type of gasifier is that its high thermal inertia and vigorous mixing enables it to gasify different types of fuel, e.g. different types of biomass depending on the seasonal condition. This is therefore one of the preferred technologies for large-scale biomass gasification plants (Basu, 2010; Ruiz, 2013).

2.7.3 Entrained flow gasifiers

Entrained flow gasifiers are the most successful and widely used gasifier type for large-scale gasification of coal, petroleum coke, and refinery residues (Basu, 2010). It is less attractive for biomass because of moisture content present in biomass feedstock (Kirkels, 2011).

Entrained bed reactors are preferred in integrated gasification combined cycle (IGCC) plants. They operate at around 1400^0C and with the pressure of between 20 and 70 bar, entraining powdered fuel through the gasifying medium. Powdered fuel (<75 μm) is injected into the reactor chamber along with the gasifying agent (Ruiz, 2013). The fuel is mixed with a paste in water to make it easier to feed into the reactor, especially if it is pressurized. When oxygen enters this type of reactor it reacts rapidly with the volatile materials and the char, producing exothermic reactions. These reactions lift the temperature above the melting point of the ash, thus completely destroying the tars or oils which is a big advantage. The high temperature also results in a higher level of conversion of carbon (Basu, 2010).

Figure 18 shows schematically two entrained-flow gasifier types. In the first one, oxygen, the most common gasifying medium, and the powdered fuel enter from the side; in the second one they enter from the top position.

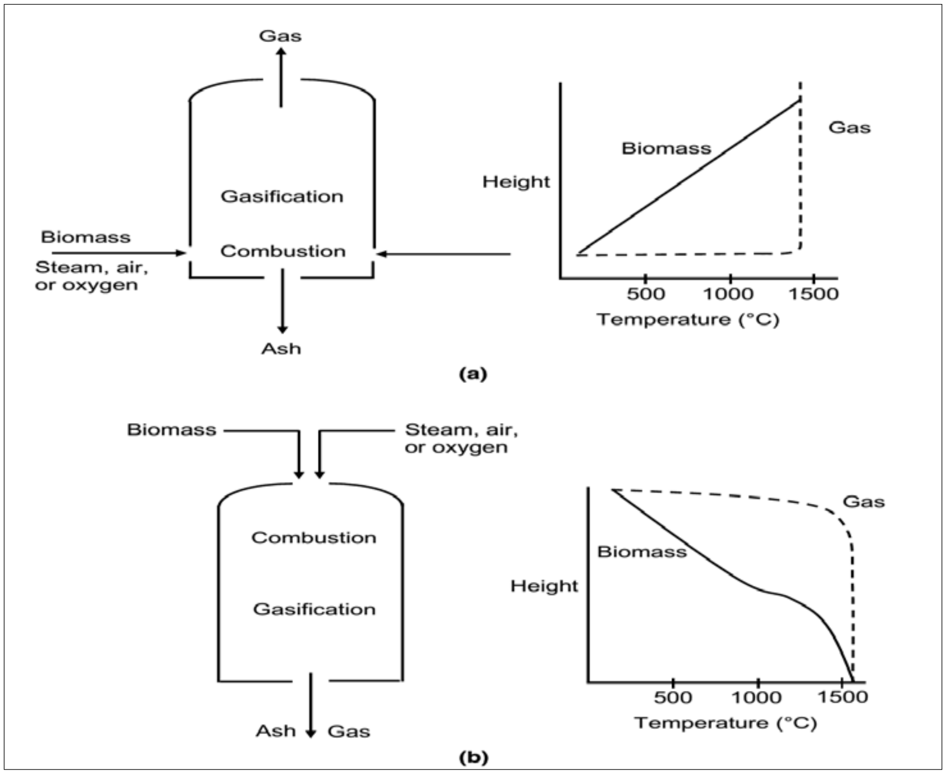


Figure 18 Two main types of entrained flow gasifiers: (a) side-fed entrained flow reactor and (b) top-fed entrained flow reactor (Source: Basu, 2010)

The summary of the notable features and comparative evaluation of fixed bed, fluidized bed, and entrained flow gasifiers is presented in Table 8 and Table 9.

Table 8 Considerations about the main types of gasifiers (Source: Arena, 2012; Coronado, 2011; Bridgwater, 1995; Kramreiter, 2008; Puig-Arnavat, 2010; Basu, 2010; Ruiz, 2013; Shafie, 2012; Roos, 2010)

Gasifier	Downdraft	Updraft	Bubbling Fluidized Bed	Circulating Fluidized Bed	Entrained Flow	Twin Fluidized Bed
Technology	Simple and proven, a simple reactor with relatively low investment cost		Plants with higher investment costs Proven technology with coal		Complex construction	
Biomass particle size (mm)	<50	6-100	<6	6-50	<0.15	<6
Fuel moisture content (wet %)	<20	Up to 50-55	<55	15-50	<15	11-25
Gas LHV (MJ/Nm^3)	4.5-5.0	5-6	3.7-8.4	4.5-13	4-6	5.6-6.3
Tars (g/Nm^3)	0.015-3.0 Very low	30-150 Very high	3.7-61.9 Average	4-20 Low	0.01-4	0.2-2
Ash and particles in syngas	Low	Moderate	High	Very high	Low	High
Reaction temperature	1000°C	1000°C	800-1000°C	1000°C	1990°C	800-1000°C
Ash melting point	>1250°C	>1000°C	>1000°C	-	>1250°C	>1000°C
Syngas output temperature	700-800°C	200-400°C	800-1000°C	850°C	>1260°C	800-1000°C
Admissible powers	Up to 1 MW_e	Up to 10 MW_e	2-50 MW_e	5-100 MW_e	>100 MW_e	2-50 MW_e
Residence time	Particles are in bed until its discharge		Particles spend substantial time in bed	Particles pass repeatedly through the circulation loop (few seconds)	Very short (few seconds)	Particles spend substantial time in bed
Carbon conversion efficiency	High	High	High. Loss of carbon in ash.	High	High	High
Process flexibility	Very limited Any change in process variables needs a new design		Flexible to loads less than design		Very limited Size and energy content of the fuel must be in a narrow range	Flexible to loads less than design
Temperature profile	High gradients	-	Vertically almost constant Little radial variation	Vertically almost constant	Temperatures above the ash melting temperature	Constants in each reactor
Hot gas efficiency	85-90%	90-95%	89%	89%	80%	90-95%

Table 9 Summary on salient features and comparative evaluation of different biomass gasifiers (Source: Ruiz, 2013; Coronado, 2011; Buragohain, 2010; McKendry, 2002; Beenackers, 1999; Roos, 2010)

Gasifier type	Salient features	Gasifier type	Salient features
Downdraft	Fuel specificity in terms of both type and size Suitable for biomass with low moisture content Producer gas with moderate calorific value and low tar and ash (or particulates) content High exit gas temperature (800^0C) Suitable for capacity 10-2000 kW_e High residence time of solids High overall carbon conversion Limited scale-up potential Easy to control	Updraft	Low exit gas temperature High thermal efficiency Producer gas with moderate calorific value but high tar and ash (or particulates) content High residence time of solids High overall carbon conversion Necessity of extensive gas cleanup before being used in gas engines Suitable for capacities up to 10 MW_e Can handle high moisture content Small and medium scale operation
Bubbling fluidized bed (BFB)	High fuel flexibility in terms of fuel type Require small particle size Flexibility of operation at lower loads than design load Ease of operation than CFB Can tolerate high ash containing feedstock Good temperature control and high reaction rates Good gas-solid contact and mixing In-bed catalytic processing possible Producer gas with moderate HHV but low tar levels and high particulates Carbon loss with ash High conversion efficiency Suitable for medium-scale capacities Good scale-up potential	Circulating fluidized bed (CFB)	High fuel flexibility in terms of both size and type Flexibility of operation at lower loads than design load Ease of operation Can tolerate high ash containing feedstock Good temperature control and high reaction rates In-bed catalytic processing possible Producer gas with moderate tar levels but high particulates High carbon conversion Good gas-solid contact and mixing Suitable for medium to large-scale capacities High conversion efficiency Very good scale-up potential Smaller in size than BFB
Entrained flow	Relatively complex construction and operation Fuel specificity in terms of particle size (costly feed preparation) Low feedstock inventory High temperature give good gas quality Materials of construction problems with high temperature Good gas-solid contact and mixing Producer gas with moderate HHV and low tar content High conversion efficiency Suitable for very high capacities (>100 MW_e) Very good scale-up potential	Twin fluidized bed	Relatively complex construction and operation Producer gas with moderate HHV and moderate tar levels Cleaning of gas before firing into engines required In-bed catalytic conversions possible Good gas-solid contact and mixing Relatively low efficiency Suitable for high specific capacities (>10 MW_e) Good scale-up potential but relatively complex design

2.7.4 Recent trends in gasification technologies

There are some gasification technologies currently under development. Two of these are briefly discussed in the following section.

2.7.4.1 Plasma gasification

Plasma gasification is a kind of gasification process, which decomposes biomass hydrocarbons into basic components, such as H_2, CO, and CO_2 in an oxygen deficient environment at an extremely high temperature (Zhang, 2010). Plasma is regarded as the 4th state of matter. It is basically any gas in which at least part of the atoms or molecules are partly or fully ionized by electric discharges. It is formed when an electric arc is generated by passing an electric current through a gas. This results in high temperatures in the plasma current which make any molecule within that current break its bonds, thus generating a syngas (Ruiz, 2013). At the same time the melting of inorganic components (glass, metal, silicates and heavy metals) gives rise to a slag that amalgamates on cooling. Plasma gasification processes may reach temperatures from 3000 to 15,000^{0}C (Zhang, 2010). Under such extremely elevated temperature, the injected biomass stream can be gasified within a few milliseconds without any intermediate reactions. In addition to the conversion of complex organic compounds into simple molecules (H_2, CO, and CO_2), other products including molten metals, vitrified inorganic compounds are also formed (Rezaiyan, 2005; Lemmens, 2007).

The plasma technique has high destruction and reduction efficiencies. Any form of wastes, e.g., liquid or solid, fine particles or bulk items, dry or wet, can be processed efficiently. But, this technology is used mainly for organic municipal solid waste (MSW) and other wastes such as paper, plastics, glass, metals, textiles, wood, rubber etc (Roos, 2010; Arena, 2012). In addition, it is a clean technique with little environmental impact. Plasma technique has great application potential for treating a wide range of hazardous wastes (Zhang, 2010). During the plasma gasification process, the toxicity of the waste can be significantly reduced, and some of the mineral compounds are converted into vitrified slag that can be utilized in road construction or landscape design (Rezaiyan, 2005; Zhang, 2010).

There are systems currently under research that have a fluidized bed gasifier and a plasma process arranged in series (Morrin, 2012). A typical plasma reactor provides comparatively a long residence time for the gas in the gasifier. The long residence time and the high temperature cause the tar products to be cracked and harmful products like dioxin and furan to be destroyed completely (Basu, 2010).

Although the main application of plasma gasification is currently focused on to treat non-biomass solid wastes, plasma gasification has been considered as a potential thermo-chemical approach for syngas production owing to its high H_2 and CO yields and extremely low tar generation capability (Lemmens, 2007; Zhang, 2010).

2.7.4.2 Supercritical water gasification

Water exists in three states under normal conditions: solid, liquid, and gas. When the pressure and temperature are increased to or above their critical points (22.1 MPa and 374^{0}C), water goes into supercritical state, where the gas and liquid phases are miscible (Zhang, 2010). Supercritical water (SCW) has found many applications in recent years due to its unique properties. It has the unique ability to dissolve materials that are normally insoluble in either ambient liquid water or steam and has complete miscibility with the liquid/vapor products from the processes, providing a single-phase environment for reactions that would otherwise occur in a multiphase system under conventional conditions. The advantages of a single supercritical phase reaction medium are likely in the sense that the inter-phase mass transport processes that could slow down reaction rates are eliminated (Zhang, 2010).

This process makes use of the conditions of the critical point of water at 647.3K and a pressure of 22.1 MPa as a favorable environment for wet biomass gasification reactions (Chen, 2010). Gasification systems with supercritical water are currently the subject of research, with satisfactory results (Chen, 2010). This system can be used not just for treating wet biomass but also for treating liquid effluent from gasification plants. According to an experiment conducted by DiBlasi et al. (2007), with products generated during gasification in an updraft reactor processing woody materials verified this. Hydrothermal gasification with supercritical water is another remarkable process, since it enables waste with high moisture contents to be processed without prior drying (Kruse, 2010).

Recently, supercritical water has accepted consideration as an ideal gasification medium for biomass primarily because of its strong solubility for organic compounds, and for its high reactivity. When water moves into the supercritical region and the pressure is maintained at a relatively low value (while still above its critical pressure, i.e., 22.1 MPa), free-radical mechanisms would replace by ionic mechanisms in the system and thus the formation of tar can be minimized significantly (Zhang, 2010).

Compared to other conventional gasification processes, supercritical water gasification provides a higher gasification efficiency and hydrogen yield, with a lower tar formation (Demirbas, 2004). Additionally, as wet biomass can be gasified directly, the expensive and energy-intensive drying process can be ignored (Roos, 2010). Moreover, due to the high pressure of the reaction, the reactor can be compact, and the hydrogen gas product can be pressurized, which is convenient for storage and transportation (Demirbas, 2004). However, similar to the conventional gasification process, the addition of a small quantity of catalyst to a biomass supercritical water gasification process can enhance gasification efficiency and hydrogen yield, especially at low reaction temperatures (Zhang, 2010).

2.7.5 Summary on biomass gasifiers

The following general technical points can be made concerning the types of biomass gasifier widely used for energy generation:

- Fixed and fluidized bed gasifiers cannot achieve high biomass conversion rates, they produce syngas with a low calorific value and their tar content is higher (Zhou, 2009).
- Downdraft or co-current gasifiers produce fewer amounts of tars than updraft or counter-current gasifiers (Son, 2011). Fluidized bed gasifiers produce intermediate tar quantities between the two. Downdraft gasifiers are more sensitive to fuel types and have little flexibility in this regard (Ruiz, 2013; Zhou, 2009)

- Downdraft gasifiers were broadly studied at experimental level by Perez et al. (2012). Report concluded that the quality of the syngas produced could be improved by increasing the diameters of the used gasifiers.
- Updraft gasifiers are suitable for applications where heat must be generated but the existence of tars is not very important (Beenackers, 1999).
- Fluidized bed gasifiers have the advantage that they allows for maintaining uniform temperatures just below problematic levels that could lead to sintering or a build-up of ash. They produce less char than fixed bed reactors, but could find it difficult to entrain certain particles, which reduces the biomass conversion efficiency (Wang, 2008). This provides high mixing and reaction rates, allows variation in fuel quality, and scaling-up of the process, making it ideal for processing of biomass and waste (Gomez, 2013).
- There are several factors to be taken into consideration when selecting the type of gasifier for a power plant. For example, due to several advantages fixed bed gasifiers are mainly used in low-output power plants (Ruiz, 2013).

There are around 50 commercial gasifier manufacturers in Europe (Balat, 2009; Ruiz 2013), among them:

- 75% produce downdraft or co-current reactors
- 20% produce fluidized bed reactors
- 2.5% produce updraft or countercurrent reactors
- 2.5% produce other types of reactor

2.8 Overview on gas cleaning

Beside the syngas production which is the primary objective of the fixed and fluidized bed gasification process, many impurities are also produced depending on the feedstock and the selected gasifier technology (Roos, 2010). Monitoring of the particles present in these impurities (e.g. dust, fly ash, tars, ammonia, sulfur compounds and others) need to begin inside the gasifier with the selection of appropriate operating parameters, their proper design and the use of the right additives and catalysts (Cui, 2010). Consequently, this will reduce the need for a subsequent cleaning of the syngas generated (Wang, 2008). However, the economics of gas cleaning process need to be carefully assessed for each plant as the removal of impurities using a proper gas cleaning mechanism increases the capital and operating costs (IRENA, 2012).

There are two different ways of cleaning the gases generated: cold and hot. Hot cleaning systems increase gasification efficiency by around 3-4%, as the syngas carries a greater amount of energy compared to cold process (Klimantos, 2009). The main components of a gas cleaning system for the removal of dust, particles and tars are as follows (Wang, 2008; Roos, 2010):

- Cyclones
- Ceramic, textile, bag filters, etc.
- Rotating particle separators
- Wet electrostatic precipitators
- Water scrubbers

Cyclones can remove up to 90% of larger particles at acceptable cost but for removing smaller particles it requires high-temperature ceramic or sintered metal filters, or the use of electrostatic precipitators (IRENA, 2012).

Removal of finer particles can be achieved using filter bags, sintered ceramic candles or metallic candles. Wet scrubbing of gas is another common technique used for removal of particulate matter. Example of wet scrubbing techniques include spray towers, centrifugal spray towers, packed bed column scrubbers, ejector venture scrubbers, etc. (Buragohain, 2010).

Entrained bed gasifiers use an arrangement on the topmost part of the reactor to cool down the syngas and remove the tars, at which the gas passes through a cyclone, filter and condenser mounted in series (Zhou, 2009). These systems remove or capture the tars in the syngas, thereby discarding all the energy they contain.

Effective removal of tar is always a basic issue in producing gas cleaning. Tar is the name given mostly to the poly-nuclear hydrocarbons, such as pyrene and anthracene, which forms as part of the gasification process. Tar is a major problem for biomass gasification technology because it sticks to pipes and to the heat exchanger, interrupting continuous operation as well as reducing overall efficiency of power generating equipment such as gas engines and gas turbines, etc. (Son, 2011; IRENA, 2012).

The treatments that can be undertaken to control tar formation are divided into those carried out inside the gasifier (primary processes), and those carried out in the hot cleaning of the gases generated (secondary processes) (Balat, 2009). In economic terms, the primary processes inside the gasifier are mostly suitable, although they have not yet been appropriately developed. The formation of tars depends on several factors, namely (Ruiz, 2013; Taba, 2012):

- Temperature
- Gasifying agent
- Equivalent ratio
- Residence time
- Catalyst additives, such as dolomite and others, which significantly convert the tars, reducing their content in the gases generated.

The optimization of the gasifier operating conditions and the right combination of catalysts (such as nickel based catalysts, calcined dolomites, magnesites, zeolites, olivine, and iron catalysts) are the key activities in reducing tars (Buragohain, 2010).

Brandt et al. (2000) observed a reduction in tars using a modification in the gasifier design which is a two-stage gasifier with pyrolysis in stage one and gasification in stage two on a charcoal bed. A similar reduction in tars was observed by Nunes et al. (2007) in an experiment with two downdraft gasifiers in series. Qin et al. (2012) conducted an experiment with an atmospheric entrained bed gasifier at high temperatures (up to 1350^0C) that showed no formation of tars (though there was some soot) with cereal straw and wood as fuel.

The secondary methods of tar removal consist of physical and chemical treatments. One such possible solution is to “crack” the tars. Catalytic cracking or thermal cracking of the tar is used to decompose or reduce the tars downstream of the gasifier, although these methods have certain disadvantages (Han, 2008).

Wet scrubbing of the gas can remove up to half of the tar and if used in combination with a venturi scrubber then 97% of the tars removal is possible (IRENA, 2012). Another possible way of removing tars and ammonia could be using hot cleaning technology through steam or dry catalytic reforming or by catalytic means involving tar cracking/hydro cracking reactions, as well as the catalytic decomposition of ammonia to form N_2 and H_2. These processes perform ineffectively and are of limited use in large plants, and more research is required into their possible implementation (Xu, 2010). Besides these methods tests have been conducted at laboratory scale on fluidized bed gasifiers with commercial sorbents, such as ZnO, for the removal of sulfur compounds (Cui, 2010).

This is important to consider that different technologies have different tolerances to impurities, so the proper design and selection of feedstock, gasifiers, and the generating technology can help lessen gas clean-up requirements and the total capital cost for the project (IRENA, 2012).

2.9 Overview on secondary conversion technologies

The secondary conversion technologies are those that convert the intermediate form of energy which is obtained after application of primary conversion technologies (i.e. pyrolysis, gasification, combustion etc.) into useful energy form such as heat or electricity (Roos, 2010).

In this study the focus is on gasification based final products mainly electricity. In the following Table 10 a brief summary of secondary technologies that could be useful in combination with biomass gasifiers are discussed.

Table 10 Summary on biomass gasification secondary conversion technologies (Source: Compiled from Buragohain, 2010; Invernizzi, 2007; Monteiro, 2009; Salomon, 2011; Roos, 2010)

Technologies commercially available		
Secondary technology	**Primary technology**	**Operational principle**
Internal Combustion Engines (ICE) (e.g. Otto, Diesel, Gas engine etc.)	Pyrolysis Gasification	Heat produced by the combustion reaction in an internal combustion chamber drives a piston through gas expansion
Gas turbine / Biomass Integrated Gasification Combined Cycle (BIGCC)	Gasification	Clean gas is compressed before being burnt inside a combustion chamber and then expanded in a gas turbine / Biomass gasification cycle is coupled with a CHP process using a gas turbine
Microturbine	Gasification	Operational principle same as gas turbine with power output limited to <500 kW_e

Technologies under R&D		
Secondary technology	**Primary technology**	**Operational principle**
Externally-fired gas turbine	Gasification Combustion	Combustion chamber of a gas turbine is replaced by a heat exchanger
BIGCC with air bottoming cycle	Gasification	Operational principle same as BIGCC but this has a steam turbine coupled at the exhaust to reuse the waste heat
Gas turbine co-fired with fossil fuels	Gasification	Producer gas is burnt along with natural gas or coal

Biomass gasification can be used to produce heat, steam, bulk chemicals or electricity. Electricity generation could be accomplished in a variety of ways but the most effective approaches involve internal combustion engines (e.g. gas engines) or gas turbines (Roos, 2010; Bridgwater, 2002). Gas turbines are prominent for their high efficiency; low specific capital cost, especially at small scale; short start-up times by virtue of modular construction; low emissions; high reliability and simple operation (Bridgwater, 2002). Gas turbines are highly sensitive to fuel gas quality, and the fuel gas must be treated to remove contaminants. Two basic gas treatment methods have been proposed in the literature: hot gas filtration and wet gas scrubbing (Bridgwater, 2002; Roos, 2010).

Biomass integrated gasification combined cycle (BIGCC)—Biomass integrated gasification combined cycle commonly termed as BIGCC technology, or biomass integrated gas turbine technology (BIG-GT), as it is sometimes referred to, has the potential to deliver much higher electrical efficiencies than conventional biomass-fired power generation such as steam turbine technology, gas engine technology (Dornburg, 2001). This is recognized as a clean and cost-effective biomass power generation technology (Balat, 2009). BIGCC technology uses steam cycles for creating a high quality gas in a pressurized gasifier that can be used in a combined cycle gas turbine (IRENA, 2012). This technology can only be used with gasification as a primary technology because gas turbines need a gas fluid to work. The higher feedstock costs for implementation of large scale BIGCC plants and the higher capital costs due to fuel handling and biomass gasification are some important considerations (IRENA, 2012).

Combined heat and power generation (CHP)—The biomass CHP technologies include biogas and plant oil CHP plants, wood chip- and straw-fired ORC (organic rankine cycle) and steam turbine plants, wood chip-fired boilers with Stirling engine and CHP technologies based on biomass gasification (down draft gasifier with gas engine, fluidized bed gasifier with gas engine and ORC process, biomass integrated gasification combined cycle; BIGCC). Generally, the plant sizes range from 35 kW_e to 50 MW_e (Kalt, 2011). Co-generation of heat and power (CHP) generally improves the efficiency of fuel use and reduces costs compared with separate generation of heat and power (Roos, 2010; Uddin, 2007). The optimal heat capacity of biomass-fired co-generation system depends on the heat demand, assuming that feedstock is available in sufficient quantities throughout the whole duration of the conversion system (Uddin, 2007).

2.10 Summary

In this chapter an extensive literature review was conducted focusing on biomass power production using gasification technologies. At first the present situation and future expansion plan of biomass power generation was investigated. Then the main biomass energy conversion mechanisms were briefly introduced. After that the process of biomass gasification and the most common technologies used for biomass gasification were explained in details. Two most recent gasification technology named plasma gasification and supercritical water gasification were also briefly introduced.

The next section explained the syngas cleaning mechanisms that are currently applied. Then the available secondary conversion technologies were outlined. It was noticed that three electricity generation technologies are used widely in gasification power projects. These are gas turbines, internal combustion engines, and microturbines.

It was also observed that not all the technologies are suitable for scaling. For example, the fixed bed gasifiers are most suitable for small-scale plants and on the other hand fluidized bed gasifiers are best suited for medium to large-scale plants.

Finally, it was realized from the study that proper utilization of the biomass resources can play an important role in the development of a sustainable long-term energy system for any countries. Production of electricity using biomass gasification technologies provides many advantages in environmental point of view. Although gasification technologies are commercially available, more works need to be done in terms of R&D and demonstration to promote their widespread commercial use for electricity generation at different scale ranges.

3. Framework and Methodology

The framework for economic analysis of the available biomass gasification technologies for electricity production will be explained in details in this section. The research is approached from a point of view of a non-experimental quantitative analysis of the existing data that is gathered from different literature sources. The methodology of the study involves three main steps. These are:

- Selection of the most competitive biomass gasification technologies for electricity production.
- Analysis of the selected technologies based on their relative electrical efficiencies.
- Calculation of electricity production capacity and the levelized costs of energy generation (LCOE) for the selected technologies.

Here for the analysis of the third step one variable has been assumed that is the total amount of available woody biomass for electricity production. This assumed variable is considerably dependent on the location of the plant and it determines how much energy can be generated.

3.1 Selection of the gasification technologies

Regarding the selection of the biomass gasification technologies for electricity production, the commercial availability of the particular technologies is considered. The reason behind that is the possibility to have more technical data which is essential for analysis. According to Dornburg et al. (2001), the following technologies are available for gasification of biomass for energy generation which is mentioned in Table 11.

Table 11 Heat and power plant categories (Source: Dornburg, 2001)

Abbreviation	Technology	Energy carrier	Power cycle	Scales ($MW_{th\text{-}input}$)
UG/H	Updraft-gasification	Heat	---	0.1-10
DG/GE	Downdraft-gasification	CHP, Power	Gas engine	0.01-3
FBG/GE	Fluidized bed gasification-atmospheric	CHP, Power	Gas engine	3-30
BIG/CC_a	Fluidized bed gasification-atmospheric	CHP, Power	Combined cycle	10-300
BIG/CC_p	Fluidized bed gasification-pressurized	CHP, Power	Combined cycle	20-300

From Table 11, it is mentionable that downdraft gasifiers up to 3 $MW_{th\text{-}input}$ and atmospheric fluidized bed gasification up to 30 $MW_{th\text{-}input}$ are coupled with gas engines. Atmospheric and pressurized fluidized bed gasification in combination with combined cycles is operated on large scales up to 300 $MW_{th\text{-}input}$ (Dornburg, 2001). There are significant differences about the suitability of a certain technology in relation to the scale of the power plant. For small scale residential heat and power applications either updraft fixed bed or downdraft fixed bed gasifiers are used. But downdraft gasifier is more suitable for electricity production because of the low amount of tar production in the producer gas (Kirkels, 2011). For medium scale heat and power application bubbling or circulating fluidized bed gasifiers are used. Regarding the large scale applications the most efficient technology found in the study is the biomass integrated gasification combined cycle technology (BIGCC) (Faaij, 2006; Kirkels, 2011).

Based on the capability to produce electricity with greater efficiency, three technologies have been selected for further extensive evaluation. These are as follows:

- Downdraft gasification coupled with gas engine (DG/GE)
- Fluidized bed gasification coupled with gas engine (FBG/GE)
- Atmospheric/Pressurized fluidized bed gasification coupled with gas turbine combined cycle (BIGCC)

In the following sections these technologies are always referred to as DG/GE, FBG/GE and BIGCC.

3.2 Evaluation of selected technologies based on electrical efficiency

After selection of the three most competitive gasification technologies for power production, the next step is to evaluate them based on their performance in relation to the electrical efficiencies. Efficiency of a conversion technology can influence the economic feasibility. The higher the efficiency is, the less the amount of biomass would be. Consequently, the fuel cost would decrease as transportation cost would be less (Akhtari, 2014).

Electrical efficiency is defined as the ratio between useful electricity output at a specific time, and the energy value of the supplied energy source during the same time period (Larsson, 2014). The overall system electrical efficiency (η_e) is defined as:

$$\eta_e = \frac{P_{out} - P_{aux}}{Q_{f,LHV}} = \frac{P_{net}}{Q_{f,LHV}} \qquad \textbf{Equation 1}$$

Where, P_{out} represents the electrical power output of the system, P_{aux} represents the power required by some of the system components, such as compressors, pumps, blowers, electrical generator, etc. $Q_{f,LHV}$ is the energy value of the supplied fuel. Here, P_{net} represents the effective electrical power that the system can generate (Bocci, 2014).

However, in some cases and especially in plants where internal combustion engines such as gas engines are used for power generation the term P_{aux} is usually considered as negligible, then the overall electrical efficiency is simply defined as:

$$\eta_e = \frac{P_{out}}{Q_{f,LHV}} \qquad \textbf{Equation 2}$$

Where, η_e represents the system electrical efficiency, P_{out} represents the electrical power output of the system, and $Q_{f,LHV}$ is the energy value of the supplied fuel (Bocci, 2014).

A comprehensive analysis of existing electrical efficiency data available in the literature was performed. Data sources were very diverse including journal papers, conference articles, report of various renewable energy organizations etc. Data were gathered considering the electrical output power, and the thermal input power as the functional unit to correlate the different electrical efficiencies for the selected technologies. The three selected technologies are commercially available in the market of either developed or developing countries. Several authors reported efficiencies from actual practical experiences concerning these technologies. Some of them also mentioned the simulation data. Most of the reported cases mentioned that the fuel used for electricity production is the woody biomass residues. Detailed information of the data source is attached in the Appendix C. The data analysis is conducted in chapter 4.

3.3 The levelized costs of energy generation (LCOE) methodology

Techno-economic evaluation of different power generating systems is commonly used to examine the potential viability of a known technology in a new market. No technology is favorable unless it is cost-effective. The economic feasibility of biomass based power plants is highly influenced by the required costs of producing electricity (Larsson, 2014). Production cost of electricity can be calculated using several approaches. A widely accepted practice is the so called levelized costs of energy generation (LCOE), or analogous names such as average lifetime levelized generation cost (ALLGC), and levelized cost of generation (LCG) (Larsson, 2014). Among many different factors, which are involved directly or indirectly for calculating economic performance of a power plant, priority have been given to LCOE, investments, operation and maintenance costs, personnel cost, and fuel costs in this study.

The LCOE is a convenient tool for comparing the unit costs of different technologies over their economic lifetime (IEA and NEA 2010). It can be used conveniently as a ranking tool to assess the cost-effectiveness of different energy generation technologies (Branker, 2011; IEA and NEA 2010). For example, IRENA (2012 & 2013) estimated power generation costs of different renewable energy technologies around the world in 2012 and IEA and NEA (2010) did a comprehensive research on projected costs of generating electricity based on data of 190 power plants located in 21 countries using the LCOE approach.

The levelized cost is actually the net present value of total lifetime costs of the energy system, considering capital cost, operation & maintenance cost, fuel cost, equipment cost and others, divided by the total amount of energy produced over the system lifetime (Khan, 2014). When considering the energy systems which include biomass gasification, the levelized cost of energy (LCOE) depends mainly on capital cost of gasifier and gas engine/gas turbine, operation and maintenance cost of the gasifier and gas engine system, and fuel cost. Life spans of the equipments, plant availability, electrical efficiency, and discount rate are some other important factors to consider in estimating the LCOE (Khan, 2014). For simplification purposes the system degradation factor, price escalation rates, and the residual value of the plant after its life time are not taken into account (Khan, 2014).

IEA (International Energy Agency) and NEA (Nuclear Energy Agency), DECC (Department of Energy and Climate Change), CASES (Cost Assessments for Sustainable Energy Systems), NEEDS (New Energy Externalities Development for Sustainability) and EUSUSTEL (European Sustainable Electricity) all of these organizations used definitions of levelized costs of energy generation identical to the formula as presented in Equation 3 (Larsson, 2014).

$$\text{LCOE} = \frac{\sum_t \left((I_t + O\&M_t + F_t + S_t) \cdot (1+d)^{-t} \right)}{\sum_t (E_t \cdot (1+d)^{-t})} \qquad \textbf{Equation 3}$$

Here, I_t is the investment spending in the year *t*, $O\&M_t$ is the cost of operation & maintenance in the year *t*, F_t is the fuel spending in the year *t*, S_t is the supplementary expenses in the year *t*, E_t is the generation of total electrical energy in the year *t*, and d is the rate of discount. This is the basic formula used for calculation of the LCOE. In the formula expenditures for CO_2 emissions, decommissioning, refurbishment, etc. are seized in the specification ***'S'*** (Supplementary) (Larsson, 2014).

According to the study done by IRENA (2012), the boundary of analysis and the major assumptions for calculating LCOE of biomass based power plants is presented in Figure 19.

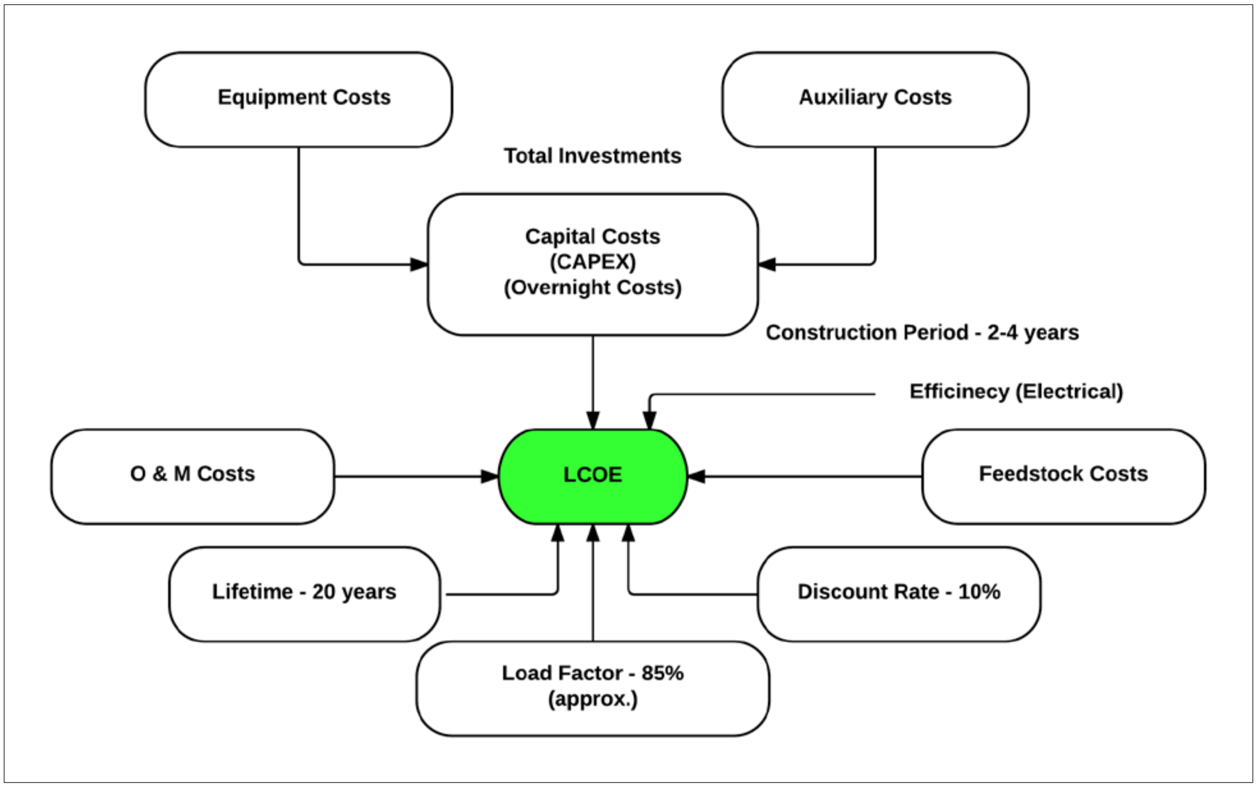


Figure 19 LCOE framework for biomass power generation (Source: Adapted from IRENA, 2012)

According to IRENA (2012), the basic information that are required to derive the LCOE from biomass-fired power generation technologies are:

- Capital costs (CAPEX)
- Discount rate
- Economic lifetime
- Feedstock costs (fuel costs)
- O & M costs
- Efficiency

- **Total plant costs (TPC) –** this is also known as total investments or capital expenditures (CAPEX) or ''turn-key'' costs. The capital cost items include the costs of the basic equipment plus costs for erection, piping, instrumentation, electrical works, civil works, buildings, engineering, management, commissioning, contingency, and interest during construction (Karellas, 2010; Bridgwater, 2002). Capital cost figures for biomass-fired plants are sensitive with the size of the particular project. CAPEX changes significantly with the capacity of the power plant. This indicates that economies of scale is an important factor when it comes to capital costs (Larsson, 2014). Another noticeable point is the differences in investments between different locations. It is very difficult to estimate how different country specific parameters such as wages, taxes, customs, shipping and price of biomass feedstock affect the capital costs and the total electricity production costs (Larsson, 2014).
- **Discount rate -** the discount rate, also known as the weighted average cost of capital (WACC), is used to calculate the present value of a stream of future cash flows. The assumption on discount rates is one of the key issues in determining the electricity production costs (Larsson, 2014; Orbaiz, 2014). The basic assumption underlying Equation1 is that the present value of all discounted power plant revenues need to be equal to the present value of all discounted power plant costs (Larsson, 2014). The discount rate used to represent the average cost of capital for biomass based power generation is assumed to be 10% (IRENA, 2012). The LCOE of a biomass-fired power plant is generally sensitive to the discount rate used for calculation.
- **Lifetime -** the economic lifetime of biomass-fired power plants is assumed to be between 20 to 25 years (IRENA, 2012).
- **Fuel costs -** the range of feedstock cost is highly site specific and also depends on some factors like transportation, storage etc. (IRENA, 2012). Throughout this study the fuel cost is not included in the variable operation and maintenance costs and is treated as a separate expense.
- **Load factor -** biomass-fired power plants are assumed to operate at an 85% load factor although the generation of a specific power plant will depend on its design and feedstock availability, quality and cost over the year (IRENA, 2012).

The O&M costs for biomass gasification based power plants are reviewed in section 3.5. The net electrical efficiency of biomass gasification plants and the specific investments required to establish a new plant are categorized in details in this study in chapter 4.

For the analysis of biomass-fired power generation in this study, certain exceptions have been considered. They are as follows:

- The CAPEX (Capital Expenditure) costs do not include grid connection, distribution systems, and transmission line costs. These costs are rather project-specific and cannot be easily generalized.
- O&M costs do not include insurance or grid charges.
- External costs (e.g. taxes and other expenses) that are not directly connected with the power plant as part of its construction or operation are not considered in this study.

3.3.1 Scope of LCOE

According to the study report of IEA and NEA (2010), LCOE methodology can be used in many applications and for many purposes. Some of these are:

- To calculate the costs of electricity production from a new plant or for a known specific technology.
- To evaluate the diverse electricity generation options available for the investors in a considered market. As the market behavior differs at different locations investors can regulate the key cost parameters along with the assumptions to better understand the local and regional market situations.
- To select the minimum investments option among possible generation technologies.
- To evaluate the influence of market transitions upon generation costs.
- To estimate the cost structure of power production options and to assess the impacts of changes in key assumptions, such as carbon prices, on unit costs.

3.3.2 Limitations of LCOE

Despite the fact that the LCOE methodology can be an efficient tool for the analysis of electricity production costs and also it gives useful insights in case of measuring investments and developing policies, at the same time, like any other computational tools, it has some real limitations, which include the followings (IEA and NEA, 2010):

- The LCOE method does not clarify the market situations characterized by uncertainties and dynamic pricing.
- It specifies generation costs at the plant level and does not cover the network costs of a power system.
- It does not provide information on the contribution of a given technology for issues such as energy security and environmental sustainability.
- It does not provide information about the probable further contribution to investments due to electricity price instability over the plant's lifetime.
- The LCOE result does not reflect the location based aspect of the investments.

3.4 Evaluation of selected technologies based on specific investments

The biomass gasification technologies that were selected for techno-economic analysis are evaluated with respect to specific investments based on the data that were found in the different literature sources. The detailed source of the gathered data is mentioned in Appendix D. the data analysis is conducted in chapter 4.

The specific investments ***(SI)*** can be defined as the ratio between the total capital costs or investments for the plant along with the electrical power output.

$$SI = \frac{I_{tot}}{E_{out}} \qquad \textbf{Equation 4}$$

Here, I_{tot} refers to the total capital costs or investments (EUR) and E_{out} is the electrical power output (MW_e).

However, to be able to compare the cost figures of selected biomass gasification technologies that were presented at different times, a common base for cost comparison is needed. Additionally, when comparing studies from different countries having different currencies, a common currency facilitates the cost comparison. Due to these reasons the cost data that was collected have been updated and converted as necessary to give all the cost figures in EUR (European Euro) based on the year 2013. The international cost indices from the Chemical Engineer (CEPCI) and Bank of Canada international exchange rates for 2013 were used for the necessary amendments of literature data in this study. The assumed exchange rates are presented in Table 12.

Table 12 Assumed exchange rates (Source: Bank of Canada official website)

Exchange rate used for cost amendment	
1 USD	0.74 EUR
1 GBP	1.24 EUR
1 SEK	0.11 EUR

Estimation technique used for capital costs

There are two main techniques that are used for estimating capital costs. These are factored estimation techniques and unit cost techniques (Crundwell, 2008). In this study report factored estimation technique is used.

Factored Estimation Technique

When the price of a product is known, either from historical data or from an analogous item of a different size, then the price can be updated for the present situation using the factored estimation technique. Factoring method estimates the cost of a product based on the cost of a reference product. For example, the costs of civil, structural and other components can be estimated as a factor of the major equipment costs (Crundwell, 2008). Most common method of factored estimation is the cost index approach. A cost index is basically the ratio of a products cost today to its cost in the past times. The Chemical Engineering Plant Cost Index (CEPCI) is the most well-known of these types of indices. The CEPCI is used for estimating power plant construction costs from one time period to another. The use of the cost index is expressed in the following formula:

$$C_n = C_p\left(\frac{I_n}{I_p}\right) \qquad \text{Equation 5}$$

Where, C_n and I_n represent the cost and the cost index as of now, respectively, and C_p and I_p represent the cost and the cost index at some previous time t_{old} (Crundwell, 2008).

For this study the CEPCI index was used for the amendment of different biomass gasification power plant investments data that were collected from the various sources during literature survey. Equation 5 is used for the amendments of data.

The CEPCI index for last 20 years is presented in Figure 20.

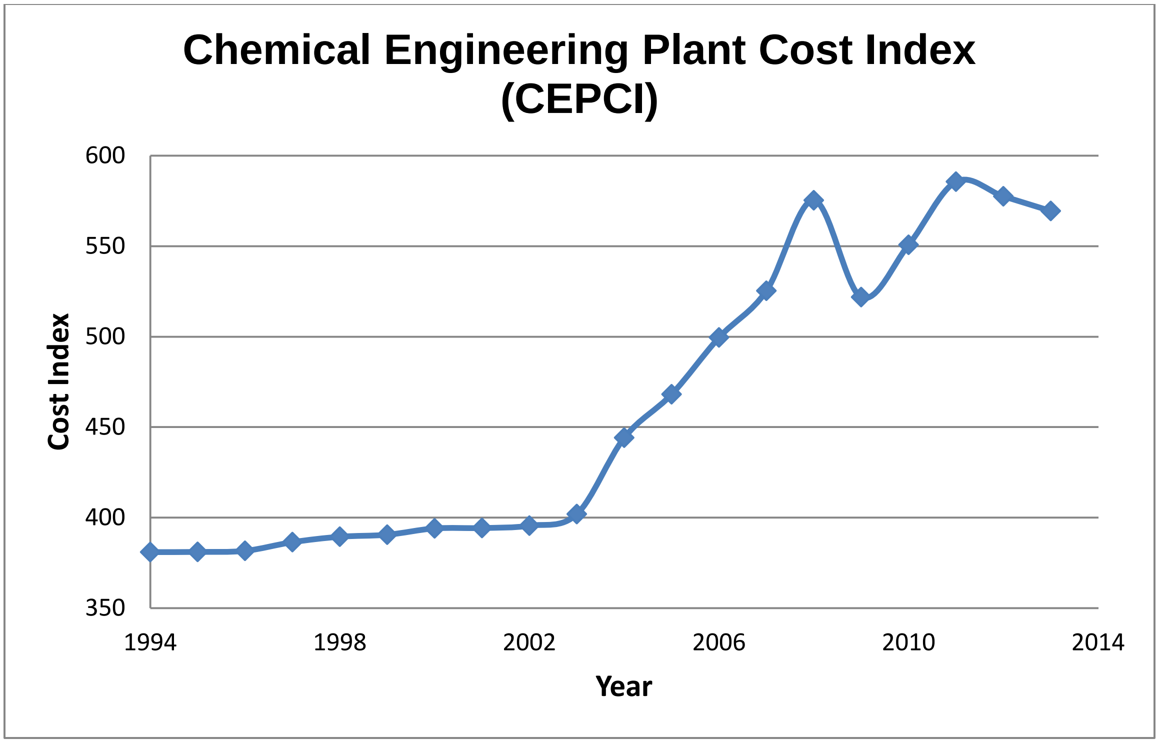


Figure 20 CEPCI index (Source: Compiled using data from website)

It is observed from Figure 20 that cost indices can change rapidly with time. Here, from the year 1994 till 2003 the cost index did not change significantly. But later there was a rapid increase till 2008. Then there were several transitions first decrease then increase till 2011 and then again a decrease in present times. For this varying nature it is important to make consideration about cost index when dealing with electricity generation cost assessments.

3.5 Overview on operation and maintenance costs of biomass plants

Operation and maintenance costs also known as OPEX (operational expenditures) refer to the fixed and variable costs that are associated with the proper functioning of biomass-fired power generation plants. O&M costs may vary significantly by project size, country and region, and depending on other economic factors (IRENA, 2012).

Fixed O&M costs often calculated as a percentage of total investments or capital costs. For biomass-fired power plants, usually these costs range from 1-6% of the initial CAPEX per year (IRENA, 2012). Basically, this is dependent on the type and scale of operation of the plant, the processing conditions, the maturity of the technology and the type of equipments used for production (Crundwell, 2008).

Fixed O&M costs include personnel or labor cost, scheduled maintenance, routine component/equipment replacement (for boilers, gasifiers, feedstock handling equipment, etc.), insurance costs, etc. The larger the capacity of the plant, the lower is the specific (per kW_e) fixed O&M costs, because of the impact of economies of scale (IRENA, 2012).

Variable O&M costs depend on the output of the system and are usually expressed as a value per unit of output (EUR/kWh$_e$). They include non-biomass fuels costs, ash disposal, unplanned maintenance, incremental servicing costs etc (IRENA, 2012). The data available in literature often combine fixed and variable O&M costs into one number so a breakdown between fixed and variable O&M costs is not possible always (IRENA, 2012; Crundwell, 2008).

Personnel/Labor costs - the costs of personnel can vary widely for a plant depending upon whether it is an integrated and automated process or it is a labor intensive process. These costs are highly dependent on the location of the plant (Crundwell, 2008). The labor requirement can be estimated from the amount of work that must be done to run the process. The number of labor needed for each production step can be determined from equipment suppliers and vendors, and the company's own previous experiences (Crundwell, 2008).

However, for simplified calculation purposes it can be assumed that the yearly cost of operation and maintenance (Cost$_{O\&M}$) for a biomass-fired plant comprises of personnel, maintenance and support services, internal usage of electricity and heat, and contingencies (if any). Furthermore, a linear proportionality relation between total investments (I) and the operation and maintenance cost (Cost$_{O\&M}$) can be assumed, and likewise, the annual operation and maintenance cost (Cost$_{O\&M}$) can be expressed as presented in Equation 4 (Faaij, 2006).

$$Cost_{O\&M} = \delta \cdot I \qquad \textbf{Equation 6}$$

Where, ***'I'*** is the total investments per kW$_e$ per year, and ***'δ'*** is a fixed fragment of this investments.

A brief summary of O&M costs literature data regarding biomass based plants is presented in the following Table 13.

Table 13 Brief overview of biomass based plants O&M costs data

Sl. No.	Reference	Biomass Conversion Technology	Remarks on O&M costs
1	Faaij et al. 1997	BIGCC	Reported O&M cost is 2% of investments assuming the normal operation of the power plant.
2	Dornburg & Faaij et al. 2001	Wood-fired thermal gasification technologies	Reported that annual O&M costs range from 3-6% of total investments. They used a value of 4% for their report.
3	Bridgwater et al. 2002	Pressurized gasification and gas turbine combined cycle	Assumed maintenance costs as 2.5% of TPC (Total Plant Cost).
4	Granatstein et al. 2004	Circulating fluidized bed gasifier	Stated maintenance cost for the 20 MW$_e$ biomass plant is 2.5% of investments/year.
5	Marbe et al. 2004	Atmospheric-BIGCC and Pressurized-BIGCC	The fixed O&M costs (% of investments/year) for both technologies to be 2.5. For both the technologies the calculated variable O&M costs is approximately 4.75 EUR$_{2013}$/MWh$_e$.

6	Dowaki et al. 2005	BIGCC	Maintenance cost was estimated as follows: Annual maintenance = plant cost × 2%
7	Faaij et al. 2006	Main conversion routes (thermo-chemical) from biomass to fuels	Operation and maintenance (O&M) cost is about 4% of the total investments.
8	Uddin et al. 2007	BIGCC CHP units	Reported the fixed O&M costs (% of investments/year) to be 2.2 approximately. For this technology the calculated variable O&M costs is approximately 8.9 EUR_{2013}/MWh_e.
9	Yassin et al. 2009	Thermo-chemical gasification systems	Estimated maintenance costs as 5% of TPC (Total Plant Cost)
10	Brown et al. 2009	Biomass gasification energy conversion systems	Speculated the maintenance cost as a parameter for levelized electricity generation cost calculation to be 5%/year of C_{GR}; where C_{GR} is the total grass root costs i.e., the total investments for a new production site.
11	Borjesson et al. 2010	BIGCC CHP plants	Calculated fixed O&M cost (% of investments/year) as 2.5 for various capacities starting from 10 MW_e up to 130 MW_e. For the calculation of variable O&M cost the estimated value is 3.4 EUR_{2013}/MWh_e.
12	Wetterlund et al. 2010	BIGCC CHP plants	Reported the fixed O&M costs (% of investments/year) to be 2.5 approximately. For this technology the calculated variable O&M costs is approximately 3.5 EUR_{2013}/MWh_e.
13	Kalt et al. 2011	DG, Gas Engine (Wood Chips)	O&M cost – 5.7% of investments of CHP plant
14	Kalt et al. 2011	FBG, Gas Engine (Wood Chips)	O&M cost – 7.5% of investments of CHP plant
15	Kalt et al. 2011	BIGCC (Wood Chips)	O&M cost – 2.5% of investments of CHP plant
16	Truong et al. 2013	BIGCC CHP units	Reported the fixed O&M costs (% of investments/year) to be 2.75 approximately. For this technology the calculated variable O&M costs is approximately 3.4 EUR_{2013}/MWh_e. For standalone BIGCC plants producing electricity the estimated fixed O&M cost is 2.5% of the investments and the variable O&M cost is 3.4 (EUR_{2013}/MWh_e).

3.6 Overview on fuel costs of biomass plants

Fuel is any material that is capable of delivering energy if it’s chemical or physical structure is changed or converted. Fuels can release energy through chemical means, such as burning, or nuclear means, such as nuclear fission or nuclear fusion.

The costs of generating energy for biomass-fired plants largely depend on the fuel costs. Fuel cost involves capital that is spent for the provision of feedstock necessary for power plant operation. It may include costs of extraction or mining, transportation and possible fuel processing to be used in a power plant. It may also incorporate storage and the probable disposal cost of waste produced by its use. On the other hand, fuel costs do not include the environmental costs, such as gaseous and particulate emissions. These costs are included in external costs (Chatzimouratidis, 2009).

Contrasted with solar, wind and hydro power, biomass electricity generation requires a feedstock that must be produced, collected, transported, and stored for power plant operations. In this context, secure, long-term supplies of low-cost, sustainably derived feedstocks are demanding for the good economy of biomass based power plants. Feedstock costs vary significantly depending on location of the plant and type of feedstock used for producing electricity. For example, the fuel cost is moderate when agricultural residues are used and these are transported over a short distance.

On the other hand, fuel costs can be high where significant transport distances are associated due to the low energy density of biomass feedstock (e.g. the trade in wood chips and pellets) (IRENA, 2012). Securing enough low-cost feedstock for large-scale plants where transportation is also needed is a challenging task. Among the different biomass feedstock agricultural residues like straw and bagasse from sugar cane are the lowest cost raw materials. For forest based residues, the cost is controlled mainly by the collection and transportation costs. The density of the forestry residues has a direct impact on the extent of transportation that is needed to deliver the feedstock at the plant site. Transportation distance is often limited to a certain scale considering the economy of electricity production (IRENA, 2012).

Assumptions regarding biomass based fuel costs from literature

According to Chatzimouratidis et al. (2009), fuel costs may vary considerably with time and regions due to several reasons such as demand, production and policy matters. Fuel costs contribute significantly to the overall cost of power production.

According to the study done by Karellas et al. (2010), on biogas production from agricultural waste, it was assumed that fuel cost is a part of the variable cost. It mentioned that the feedstock cost consists of three different components, these are:

1) Feedstock acquisition cost (type, location).
2) Feedstock transportation cost, from the feedstock production site to power plant gate.
3) Feedstock processing cost (milling, storage on site, etc.).

It was mentioned that the estimation of the feedstock cost is highly project specific and an exhaustive and thorough feedstock assessment should be undertaken to determine available feedstock type and their respective costs.

According to Larsson et al. (2014), fuel costs are heavily affected by the assumptions on the fuel price and plant efficiency and both of these needs to be assessed properly. Inaccuracy concerning estimation of biomass based power plant efficiencies may affect total fuel costs because a lower electrical efficiency leads to more fuel consumption per unit of electricity produced.

International Renewable Energy Agency (IRENA, 2012) made a report on cost analysis of biomass based power generation. To calculate the levelized costs of energy generation (LCOE) from biomass they assumed the range of feedstock costs from 10 USD/t for local waste feedstock to 160 USD/t for pellets (with transportation cost included in the case of pellets).

According to the study done by Heffels et al. (2014), on environmental and economic assessment of absorption-enhanced reforming (AER) biomass gasification, regarding fuel costs, 85 EUR/t were assumed for the mixture of forest residues and landscaping material, including the transportation and delivery to the plant site. It was further assumed that fuel prices are subject to a constant increase of 3%/year.

3.7 Detailed explanation of calculation methodology of the LCOE

The most important step of this study is to calculate the levelized costs of energy generation (LCOE) for the selected biomass gasification technologies in order to compare the suitability of these technologies for a specific project. The input parameters that are needed for this calculation are introduced in this chapter. The step-by-step calculation of LCOE is discussed in the following sections.

The calculation is carried out based on some assumptions regarding input parameters and quantitative relations found in data analysis while evaluating selected technologies for electrical efficiencies and specific investments. An algorithm was developed during the study for the LCOE calculation. This algorithm was followed for creating the mathematical tool. The summarized algorithm is attached at the end of this chapter.

3.7.1 Determination of total attainable energy

To determine the total obtainable energy two parameters are required. These are:

- Available quantity of woody biomass (t/y) on dry basis—it is an assumed quantity.
- Lower heating value of woody biomass (GJ/t) on dry basis—it is considered as an average value of 17.5 GJ/t with reference from Table 2. Usually the values of LHV are given in MJ/kg in the literature but for consistency it is considered as GJ/t in this calculation.

$$E_{total} = m \cdot LHV \qquad \text{Equation 7}$$

Where, E_{total} is the total amount of obtainable energy (GJ/y), m is the available quantity of woody biomass (t/y) on dry basis, and LHV is the lower heating value of woody biomass (GJ/t) on dry basis. Then, the value of E_{total} is converted to MWh_{th}/y from GJ/y using conversion formula 1 GJ = 0.28 MWh_{th}.

3.7.2 Determination of possible electricity production and power output

To determine the possible electricity production potential (MWh_e/y) two parameters are required. These are:

- The total amount of obtainable energy referred to as E_{total} in the previous step.
- Estimated electrical efficiency (η_e)—this value is obtained using regression technique on the collected data for DG/GE, FBG/GE, and BIGCC technology respectively.

$$E_p = E_{total} \cdot \eta_e \qquad \textbf{Equation 8}$$

Where, E_p is the possible electricity production potential (MWh_e/y), E_{total} is the total amount of obtainable energy (MWh_{th}/y), and η_e is the estimated electrical efficiency.

To determine the tentative power output (MW_e) two parameters are required. These are:

- The possible electricity production potential (MWh_e/y)—referred to as E_p in the previous step.
- Total operating hours of the plant (h/y)—with reference to IEA and NEA report (2010) it was noticed that the load factor of biomass based power plants are typically considered as 85%. For this reason the operating hours is assumed to be approximately 7000 h/y for the selected biomass gasification technologies in this study.

$$P_{out} = E_p / t_o \qquad \textbf{Equation 9}$$

Where, P_{out} is the tentative power output (MW_e), E_p is the possible electricity production potential (MWh_e/y), and t_o is the total operating hours of the plant (h/y).

3.7.3 Determination of fuel cost

With reference from the literature data the biomass fuel cost is assumed to be 85 EUR/t for the calculation of LCOE which includes feedstock handling and transportation to plant's gate. To determine the fuel cost as per obtained energy (EUR/MWh_{th}) three parameters are required.

These are:

- Available quantity of woody biomass (t/y)
- Total amount of obtainable energy (MWh_{th}/y)
- Fuel cost assumed (EUR/t)

$$F_{cost} = m / E_{total} \cdot F_a \qquad \textbf{Equation 10}$$

Where, F_{cost} is the fuel cost as per obtained energy (EUR/MWh_{th}), m is the available quantity of woody biomass (t/y) on dry basis, E_{total} is the total amount of obtainable energy (MWh_{th}/y), and F_a is the assumed fuel cost (EUR/t).

3.7.4 Determination of LCOE for selected technologies

The most important input parameters required for the calculation of LCOE for the selected technologies are summarized in following Table 14. These parameters are used in the mathematical tool developed using Microsoft Excel® for the calculation of LCOE.

Table 14 Basic input parameters for LCOE calculation (Source: Own compilation from literature study)

Input parameters	Configuration	Remarks
Specific Investments (EUR/kW_e)	Investment models	For DG/GE, FBG/GE, and BIGCC technology respectively

Discount Rate (%)	10%	For all three technologies
Maintenance Rate (%/y of Invests)	4%	For all three technologies
Operating Hours per Year (h/y)	7000h/y	For all three technologies
Technical Lifetime of Plant (years)	20years	For all three technologies
Fuel Cost (EUR/MWh$_{th}$)	17.35 EUR/MWh$_{th}$	For all three technologies

Using the discount rate, which is also known as the weighted average cost of capital (WACC) the present value of money i.e. capital cost is calculated on the basis of per kW$_e$ per year. The formula is as follows:

$$I_t = I_{total} \cdot \frac{d \cdot (1+d)^{lt}}{(1+d)^{lt}-1} \qquad \textbf{Equation 11}$$

Where, ***I_t*** is the capital cost in year ***t*** (EUR/kW$_e$/y), ***I_{total}*** is the total investments for the power plant for the entire lifetime of operation discounted at t=0 (in EUR/kW$_e$), ***d*** is the rate of discount for the entire investments (%), and ***lt*** is the entire lifetime of the plant (years).

For the calculation of capital cost per kW$_e$ per year (EUR/kW$_e$/y) i.e. ***I_t*** using Microsoft Excel® the PMT function is used. The syntax for PMT function is:

PMT (rate, nper, pv, [fv], [type])

Where, ***rate*** is the equivalent term for the discount rate ***d***, ***nper*** is the equivalent term for the entire lifetime ***lt***, ***pv*** is the present value which is the equivalent term for the total investments for the power plant ***I_{total}*** (EUR/kW$_e$), ***fv*** is the future value, it is omitted in the calculation, ***type*** is an optional argument which is also omitted in the calculation.

The O&M cost is considered as a fixed fraction (4%) of the ***I_t*** which is the capital cost in year ***t*** (EUR/kW$_e$/y).

The fuel cost per kW$_e$ per year is calculated as follows:

$$F_{el} = \frac{Fcost \cdot to}{1000 \cdot \eta_e} \qquad \textbf{Equation 12}$$

Where, ***F_{el}*** is the fuel cost per kW$_e$ per year (EUR/kW$_e$/y), ***F_{cost}*** is the fuel cost as per obtained energy (EUR/MWh$_{th}$), ***t_o*** is the total operating hours of the plant (h/y), and ***η_e*** is the estimated electrical efficiency.

The electrical energy per kW$_e$ per year is calculated as:

$$E_{el} = E_p / P_{out} \qquad \textbf{Equation 13}$$

Where, ***E_{el}*** is the electrical energy per kW$_e$ per year (kWh$_e$/kW$_e$/y), ***E_p*** is the possible electricity production potential (MWh$_e$/y), and ***P_{out}*** is the tentative power output (MW$_e$).

Finally, the levelized cost of energy generation (LCOE) is calculated using the formula:

$$LCOE = [I_t + O\&M_t + F_{el,t}] / E_{el,t} \cdot 100 \qquad \textbf{Equation 14}$$

Where, $LCOE$ is the levelized costs of energy generation (ctEUR/kWh$_e$), I_t is the capital cost in year t (EUR/kW$_e$/y), $O\&M_t$ is the operation and maintenance cost in year t (EUR/kW$_e$/y), $F_{el,t}$ is the fuel cost per kW$_e$ per year (EUR/kW$_e$/y), and $E_{el,t}$ is the electrical energy per kW$_e$ per year (kWh$_e$/kW$_e$/y).

3.7.5 Algorithm developed for the calculation of LCOE

An algorithm was developed based on the calculation steps that are explained in previous sections for the determination of LCOE of the selected biomass gasification technologies is presented in the following Figure 21. This algorithm is followed in the mathematical tool developed using Microsoft Excel®. Using the tool the LCOE of the selected technologies can be calculated with different input parameters.

3.8 Summary

In this chapter the basic framework and methodology used for this study is explained. Firstly, the most competitive technologies that are available now for biomass gasification plants are selected. Then the technologies have been characterized with respect to their electrical efficiencies along with their capacity ranges.

After that the detailed methodology of levelized costs of energy generation (LCOE) is presented including the main parameters associated for the calculation. Next the selected technologies are evaluated based on their specific investments. The study showed the significant role of scale effects within biomass energy systems.

In both the cases i.e. efficiency and specific invests economies of scale has been observed which implies the bigger is the power plant the higher is the electrical efficiency and the bigger is the power plant the lower is the investments required. The overview on operation and maintenance cost (O&M) and fuel cost for biomass power plants are outlined consequently in later sections. The evaluation that is made and relations (i.e. efficiencies, specific investments) found in this chapter are vital sources for the calculation of LCOE of the selected biomass gasification technologies.

Finally, it is noticed that in order to choose the best technological option of setting up a new biomass based power plant, several costs should be taken into account. These costs are the capital costs, the O&M costs, the fuel costs and the external costs (if any).

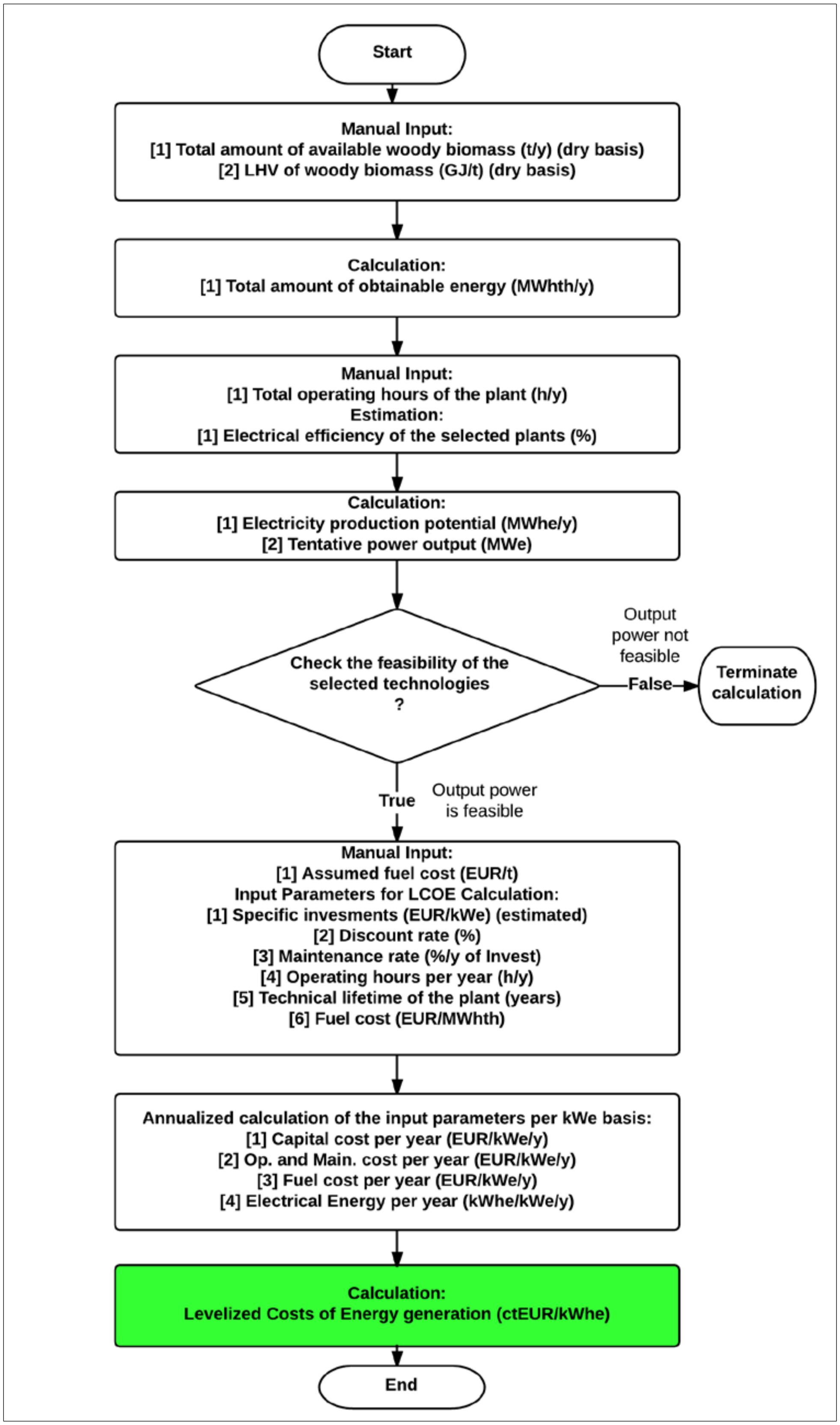


Figure 21 Algorithm developed for the calculation of LCOE

4. Data analysis, Results and Key findings

In this chapter the analysis of electrical efficiency and specific investments data is carried out using several plots. The results of levelized costs of energy generation are compared for the selected biomass gasification technologies. A detailed sensitivity analysis is performed at the end and two study cases are conducted to compare the LOCE results.

However, it is also noteworthy to mention that significant amount of time was invested for the collection of literature data regarding electrical efficiencies, and specific investments of the selected biomass gasification technologies to make the LCOE calculation reasonable.

4.1 Electrical efficiency models

The electrical efficiency of the selected biomass gasification technologies are modeled using regression technique on the gathered data. The collected data are listed in Appendix C.

All the electrical efficiency data collected from different sources for the selected technologies are presented in the following plots from Figure 22-27 with respect to power plant capacity.

The following equations were found after regression to best fit the data in the graphs and these equations are used for the estimation of electrical efficiencies of the technologies during the calculation of LCOE.

$$\boldsymbol{\eta^{e}_{DG/GE} = 0.2905\ Q^{0.1191}}$$ **Equation 15**

$$\boldsymbol{\eta^{e}_{FBG/GE} = 0.2223\ Q^{0.1351}}$$ **Equation 16**

$$\boldsymbol{\eta^{e}_{BIGCC} = 0.2896\ Q^{0.072}}$$ **Equation 17**

Where, ***Q*** is the electrical output capacity of the plants (MW_e).

Upon close observation it can be inferred that all the distributions show somehow a similar pattern (although there are few exceptions) as anticipated which is the bigger is the power plant input/output the higher is the electrical efficiency. Some authors mentioned the electrical efficiency data based on LHV of fuel used whereas some mentioned data based on HHV of fuel used. For some cases it is not explicitly mentioned on which basis the efficiency was calculated. These are the reasons behind some irregularities in the graphs.

However, there observed to be some technological limits to the efficiency values. For small and medium scale technologies the standard electrical efficiency is slightly less than 30% or slightly above 30% respectively. On the other hand, for large scale technologies the threshold value of electrical efficiency is about 43%.

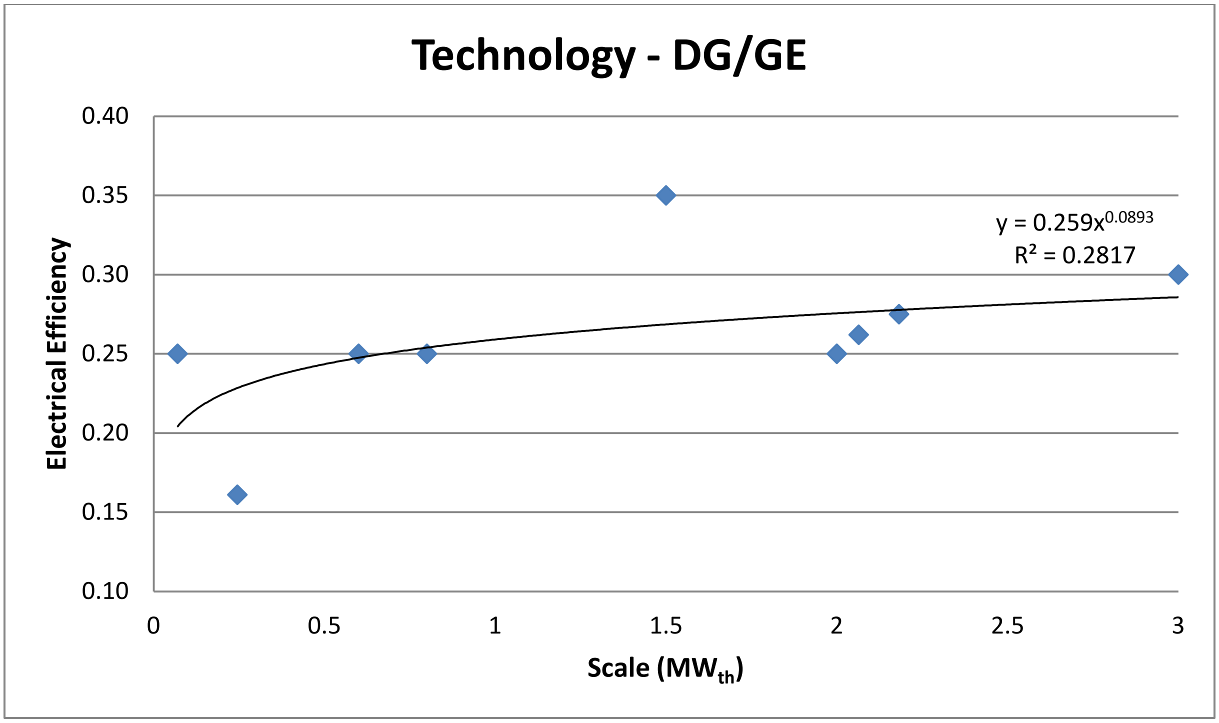


Figure 22 Electrical efficiency of DG/GE plants along thermal input scale

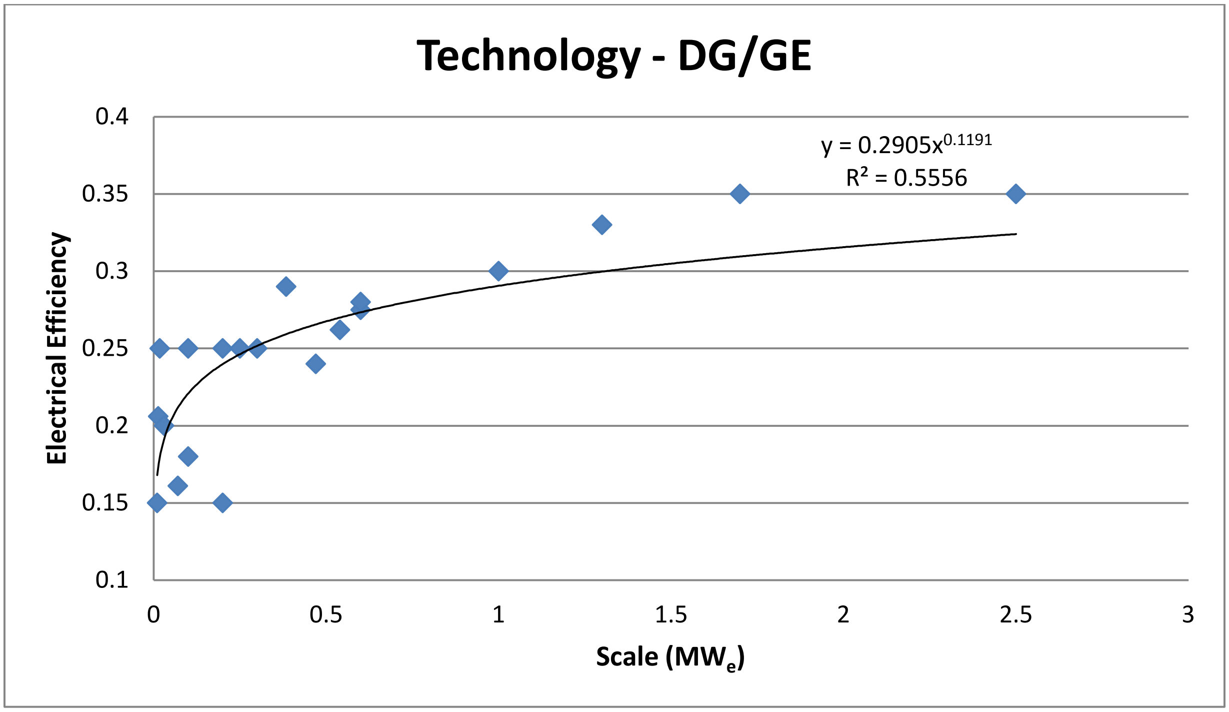


Figure 23 Electrical efficiency of DG/GE plants along electrical output scale

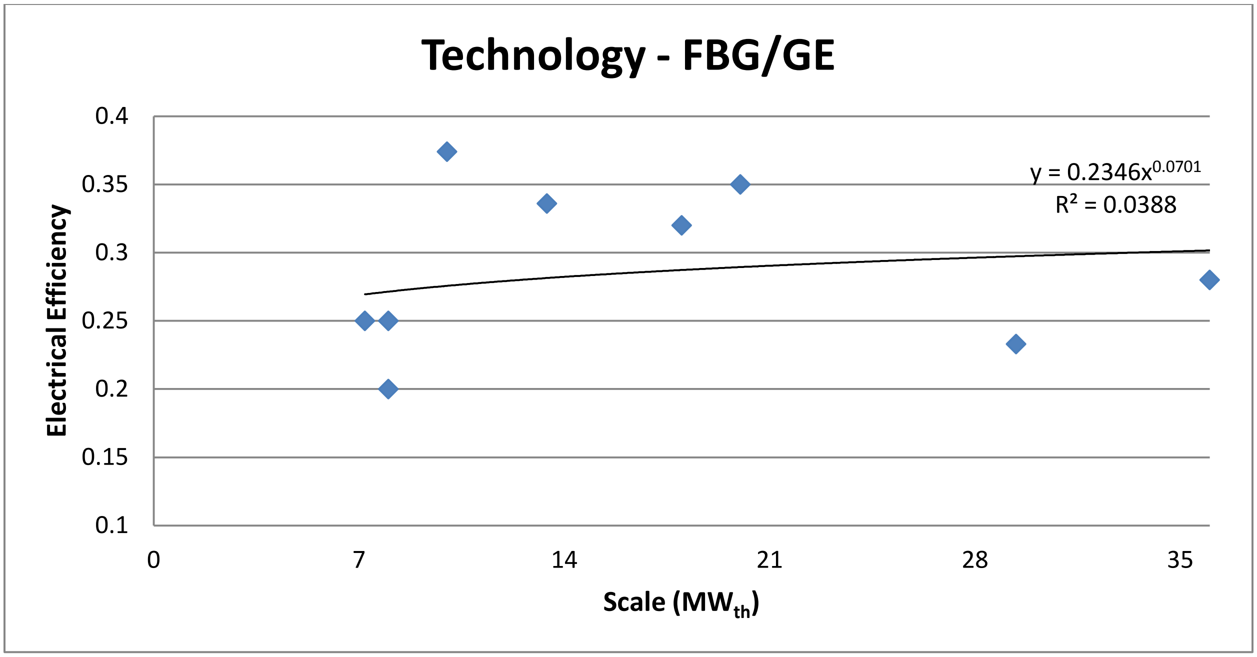


Figure 24 Electrical efficiency of FBG/GE plants along thermal input scale

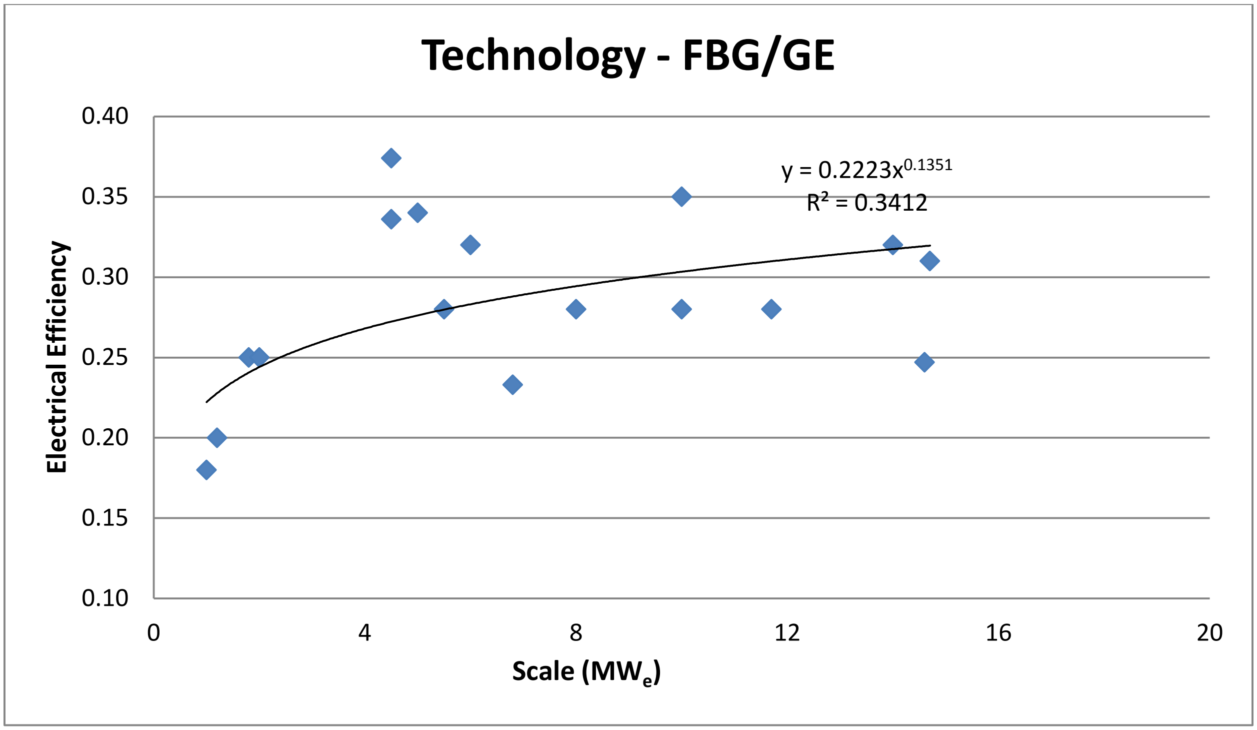


Figure 25 Electrical efficiency of FBG/GE plants along electrical output scale

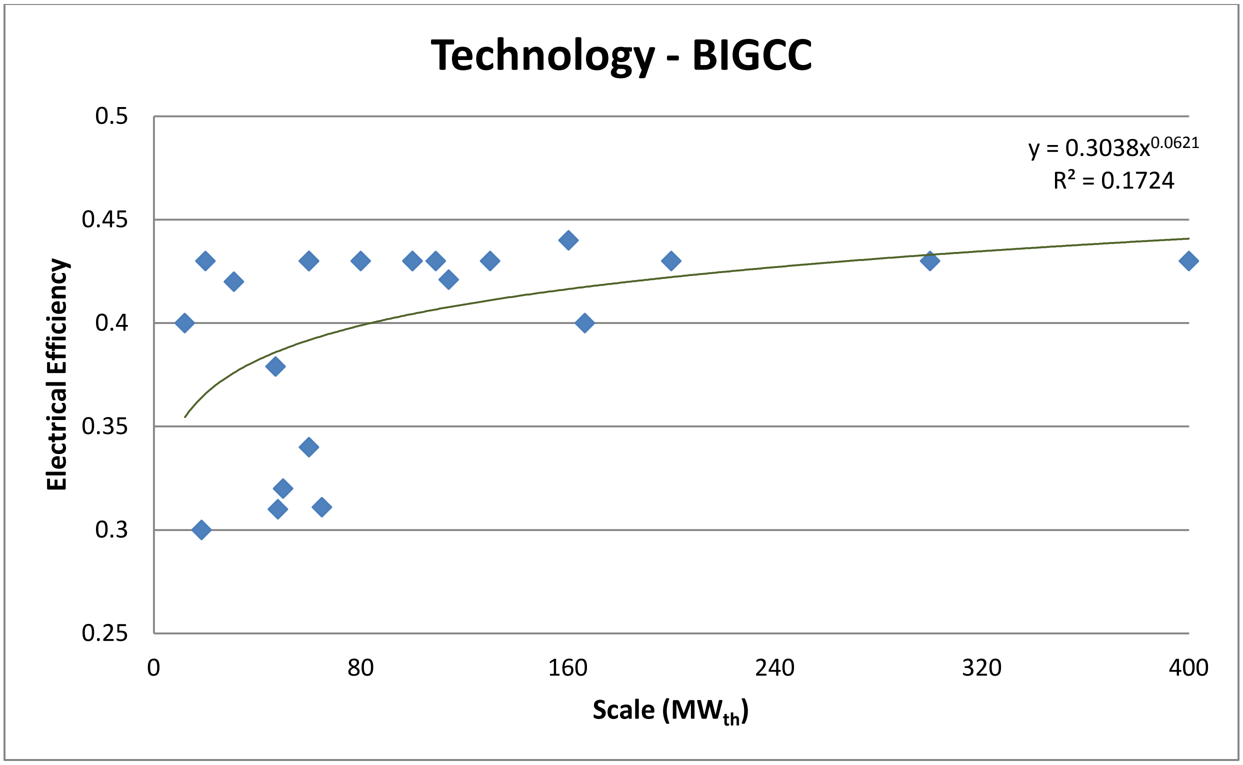


Figure 26 Electrical efficiency of BIGCC plants along thermal input scale

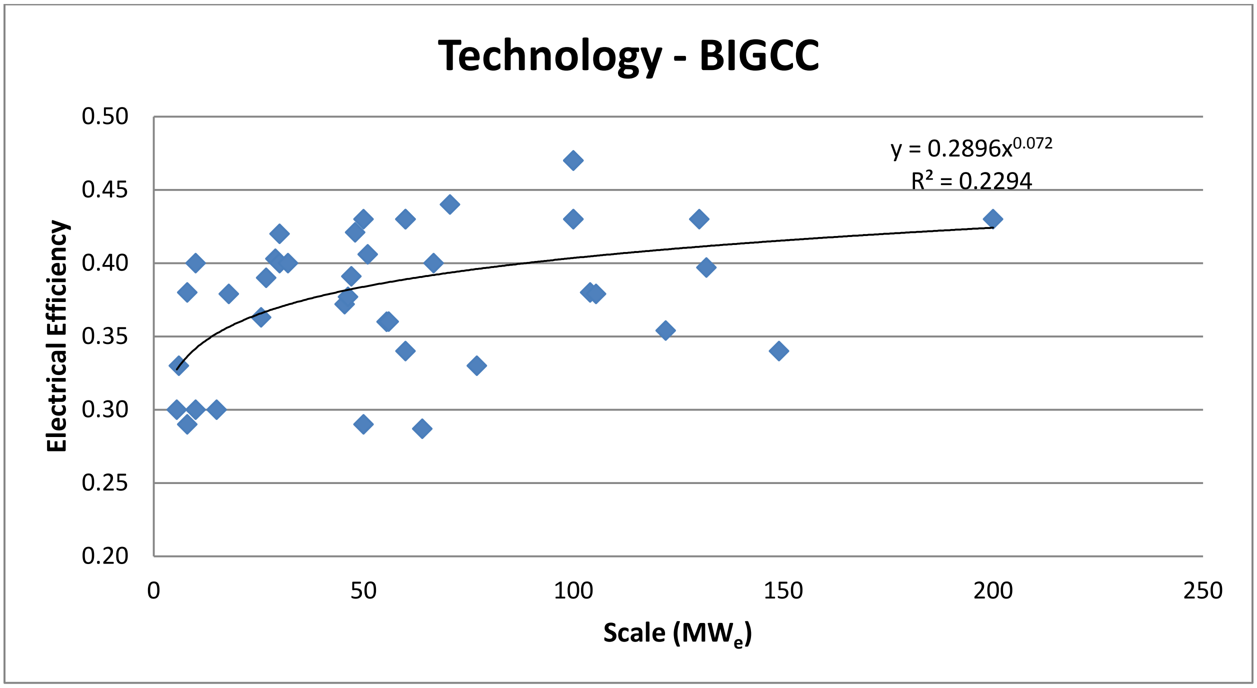


Figure 27 Electrical efficiency of BIGCC plants along electrical output scale

4.2 Specific investments models

The specific investments of the selected biomass gasification technologies are modeled using regression technique on the gathered data. The collected data are listed in Appendix D. All the specific investments data collected from different sources for the selected technologies are presented in the following plots from Figure 28-30 with respect to power plant capacity. However, the specific investments data for DG/GE and FBG/GE technologies are not that much available. It is therefore possible that the SI measures may vary substantially by including more data points.

The following equations were found after regression to best fit the data in the graphs and these equations are used for the estimation of specific investments of the technologies during the calculation of LCOE.

$$SI_{DG/GE} = 2825.5\ Q^{-0.192} \qquad \text{Equation 18}$$

$$SI_{FBG/GE} = 14666\ Q^{-0.714} \qquad \text{Equation 19}$$

$$SI_{BIGCC} = 11628\ Q^{-0.424} \qquad \text{Equation 20}$$

Where, ***SI*** represents the specific investments (EUR_{2013} basis), and ***Q*** is the electrical output capacity of the plants (MW_e).

All the graphs show a similar pattern which follows economies of scale i.e. the bigger is the power plant in capacity the lower is the specific investments required. They also reflects that for small-scale plants (capacity <3 MW_e) DG/GE is the most suitable technology, for medium-scale plants (capacity <20 MW_e) FBG/GE is the most convenient technology, and for large-scale plants (capacity >50 MW_e) BIGCC is the competitive technology.

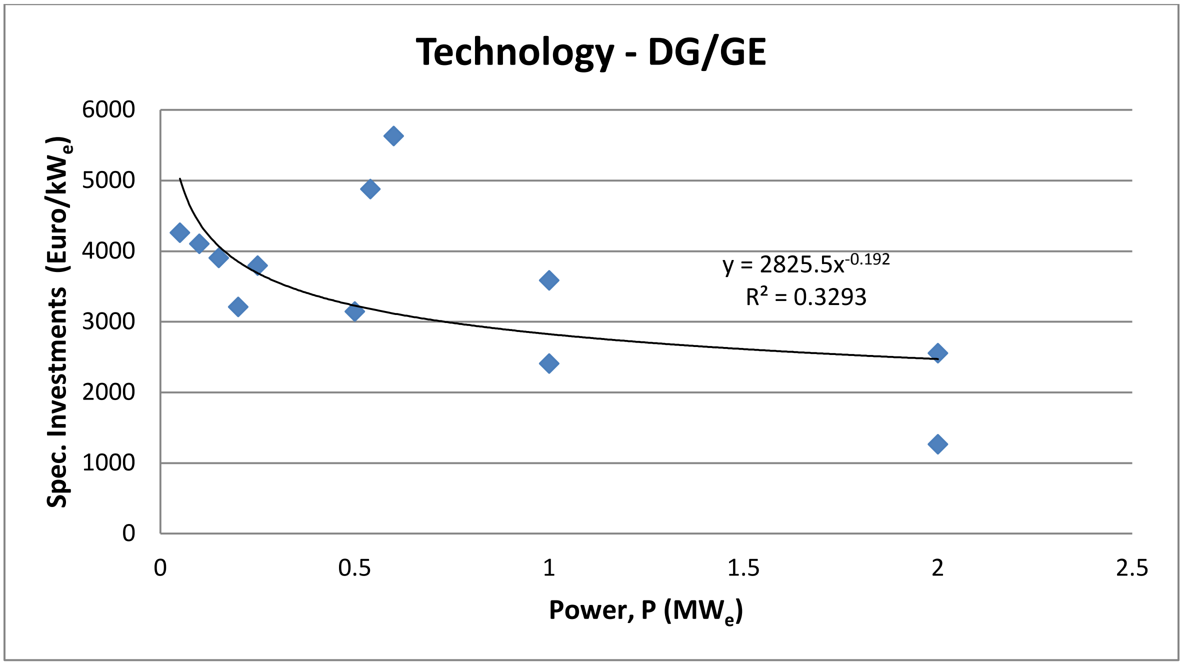


Figure 28 SI for downdraft gasification coupled with gas engine system (Scale: electrical output)

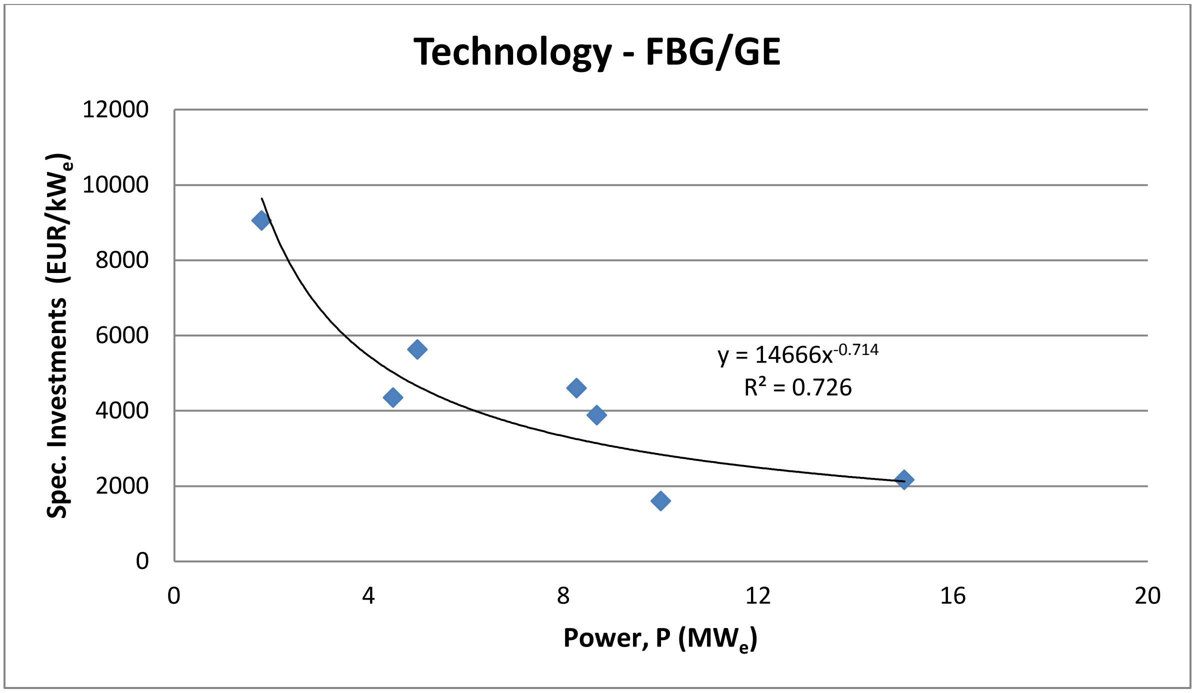


Figure 29 SI for fluidized bed gasification coupled with gas engine system (Scale: electrical output)

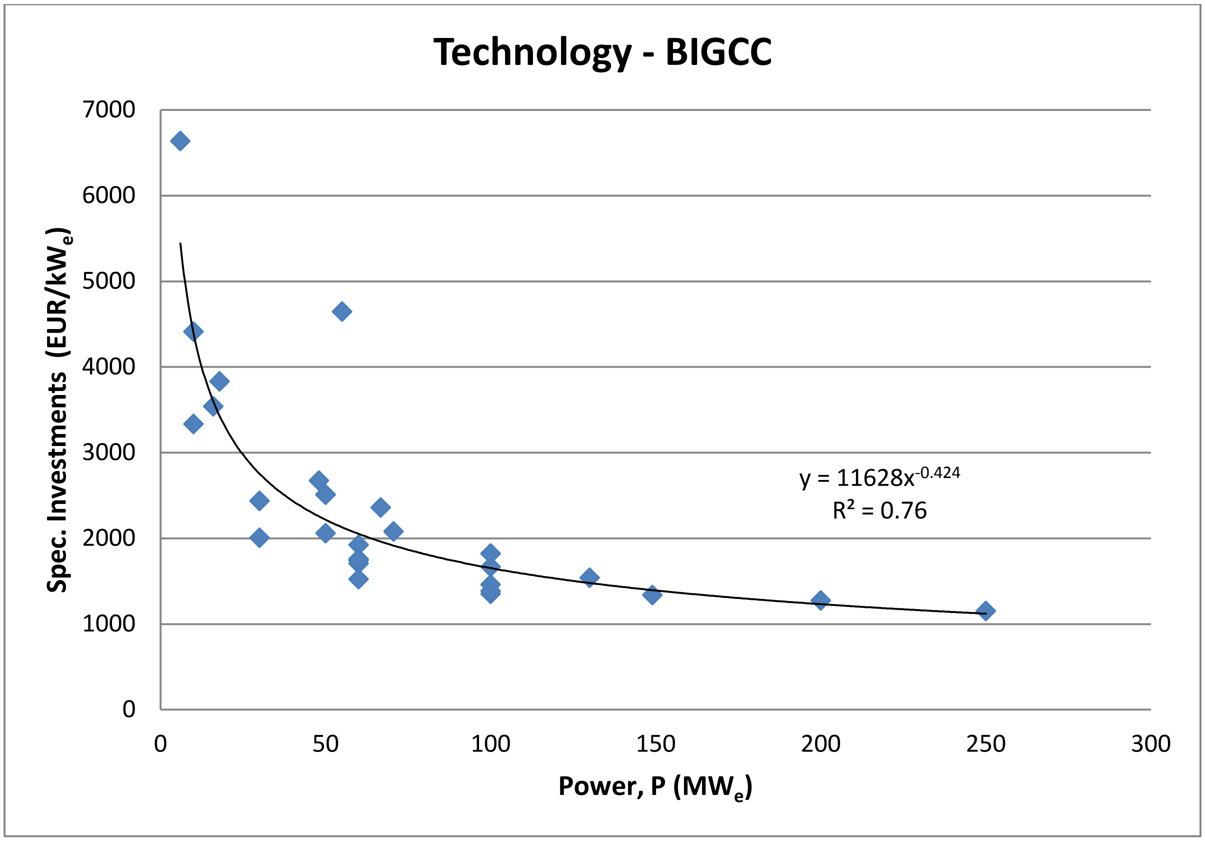


Figure 30 SI for BIGCC power plants (Scale: electrical output)

4.3 Key findings

The main results of the study and calculations are summarized in Table 15.

Table 15 Key findings regarding the selected gasification technologies

Technology	Scale range (MW_e)	Electrical efficiency (η_e)	Specific investments (EUR/kW_e)	LCOE range ($ctEUR/kWh_e$)
DG/GE	0.01-3.00	17% - 33%	2290 - 6760	10.39 - 25.46
FBG/GE	2.00-20.00	24% - 33%	1730 - 8910	9.09 - 27.15
BIGCC	6.00-300.00	33% - 44%	1035 - 5440	6.30 - 17.49

A qualitative comparison (as the fuel cost is not same for all the cases) of LCOE between the biomass-fired gasification technologies is presented in the following Figure 31. Here, DG/GE, FBG/GE, and BIGCC represent the selected technologies for this study. The other technologies are as follows:

- G+GE (L)—means gasification coupled with gas engine (literature data) (Source: Chum, 2011; amended for EUR_{2013} basis)
- F+FBG (L)—means fixed and fluidized bed gasifiers (literature data) (Source: IRENA, 2012; amended for EUR_{2013} basis)
- G+CHP (L)—means gasifier with combined heat and power (literature data) (Source: IRENA, 2012; amended for EUR_{2013} basis)
- BIGCC (L)—means biomass integrated gasification combined cycle power plant (literature data) (Source: Bauen, 2009; amended for EUR_{2013} basis)

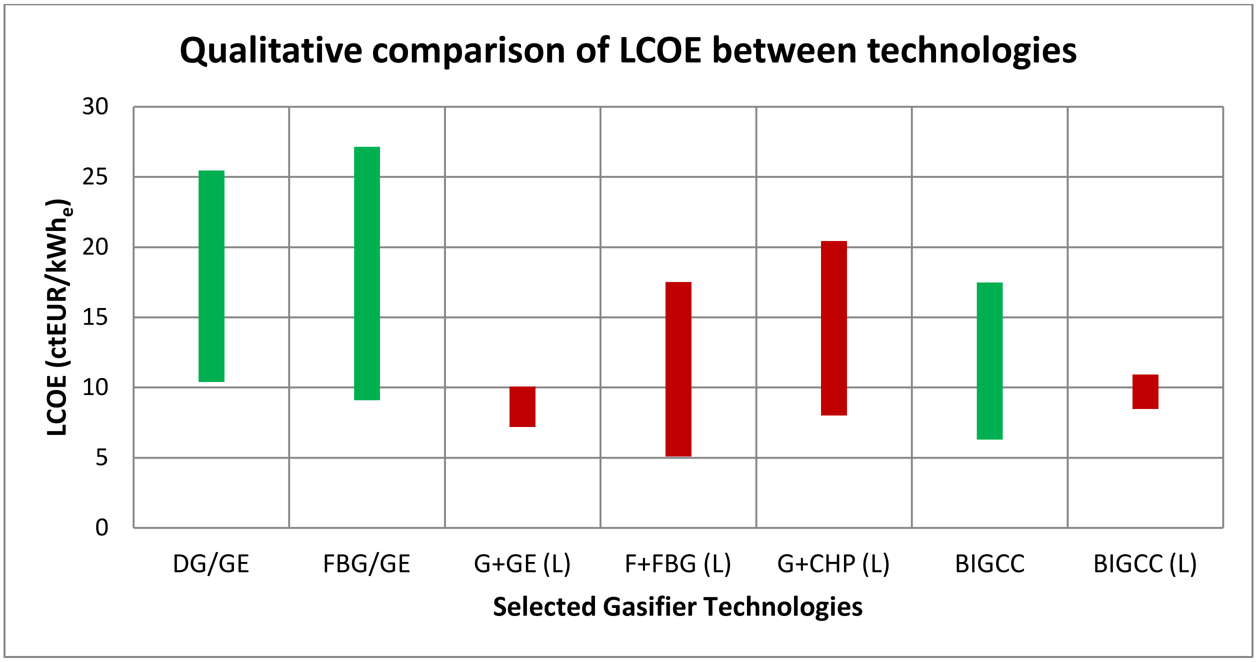


Figure 31 Comparison of LCOE range for biomass gasification based plants

A comparison of specific investments between the biomass gasification technologies is presented in the following Figure 32. Here, DG/GE, FBG/GE, and BIGCC represent the selected technologies for this study. The other technologies are as follows:

- F+FBG (L)—means fixed and fluidized bed gasifiers (literature data) (Source: IRENA, 2012; amended for EUR_{2013} basis)
- G+CHP (L)—means gasifier with combined heat and power (literature data) (Source: IRENA, 2012; amended for EUR_{2013} basis)
- BIGCC (L)—means biomass integrated gasification combined cycle power plant (literature data) (Source: IRENA, 2012; amended for EUR_{2013} basis)

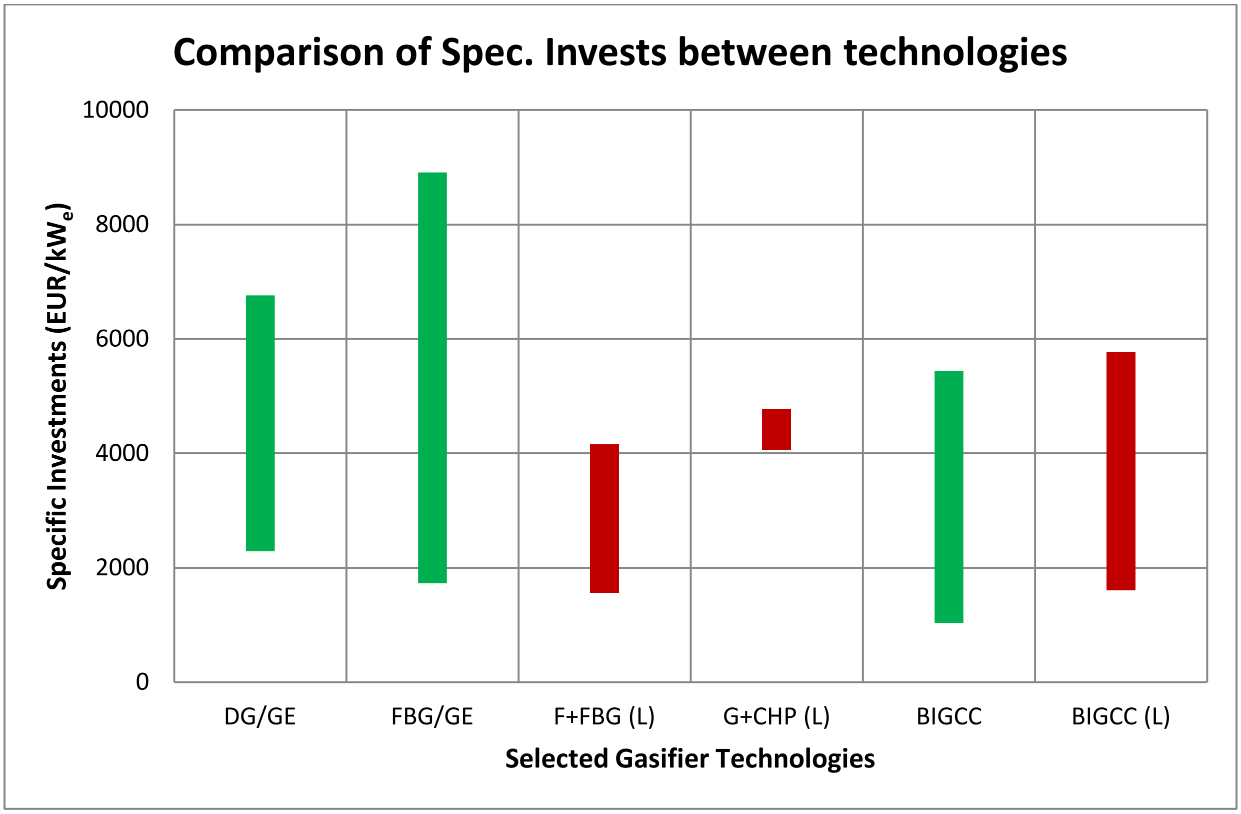


Figure 32 Comparison of spec. investments range for biomass gasification based plants

4.4 Sensitivity analysis of economic performance

Some of the input parameters that were assumed during the calculation of LCOE of the selected biomass gasification technologies have certain range of uncertainties. Discount rate, costs of fuel, and lifetime of the plant are considered here as the most uncertain parameters and these parameters are further scrutinized in Figure 33, 34, and 35. These figures show the sensitivity of the LCOE results with the variations in the assumed input values. Referring to Figure 33 and 34 it can be seen that the LCOEs show a positive correlation with the variation of discount rate and fuel cost. A negative correlation is observed with the variation of the plants lifetime. Another important observation is that the larger is the power plant in size, the less sensitive it is with the variation of the input parameters.

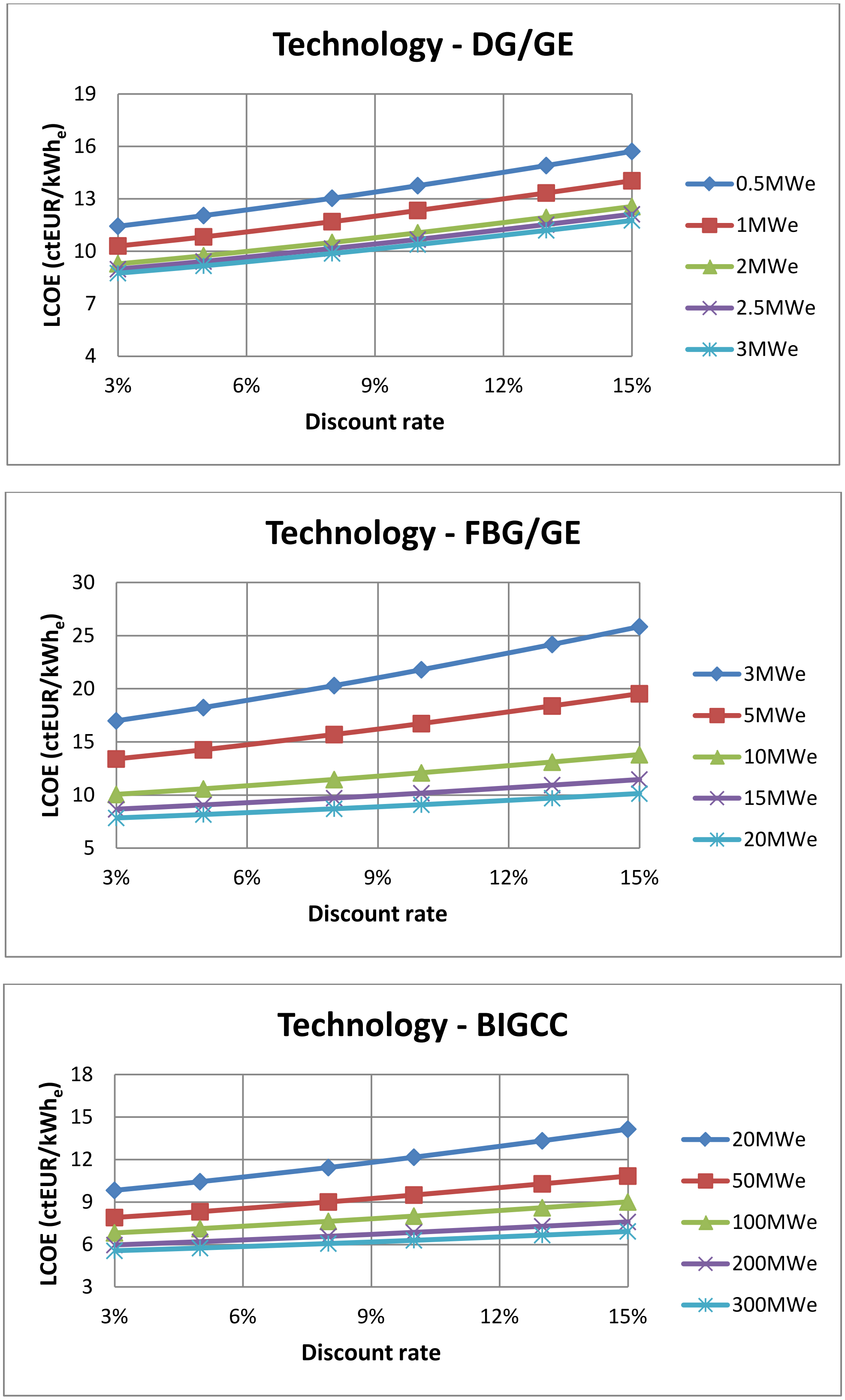


Figure 33 Sensitivity analysis regarding discount rate variation for selected technologies

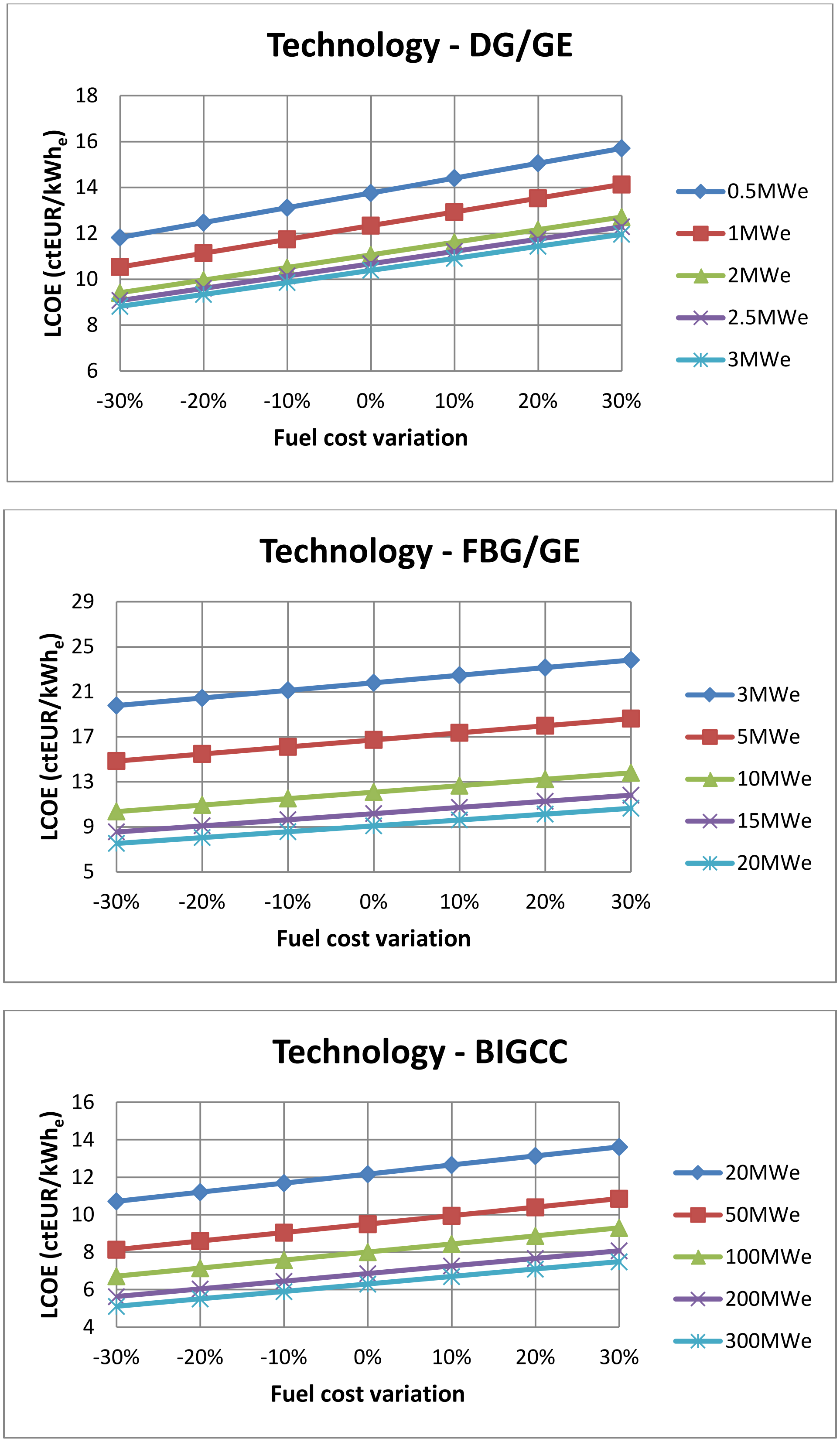


Figure 34 Sensitivity analysis regarding fuel cost variation for selected technologies

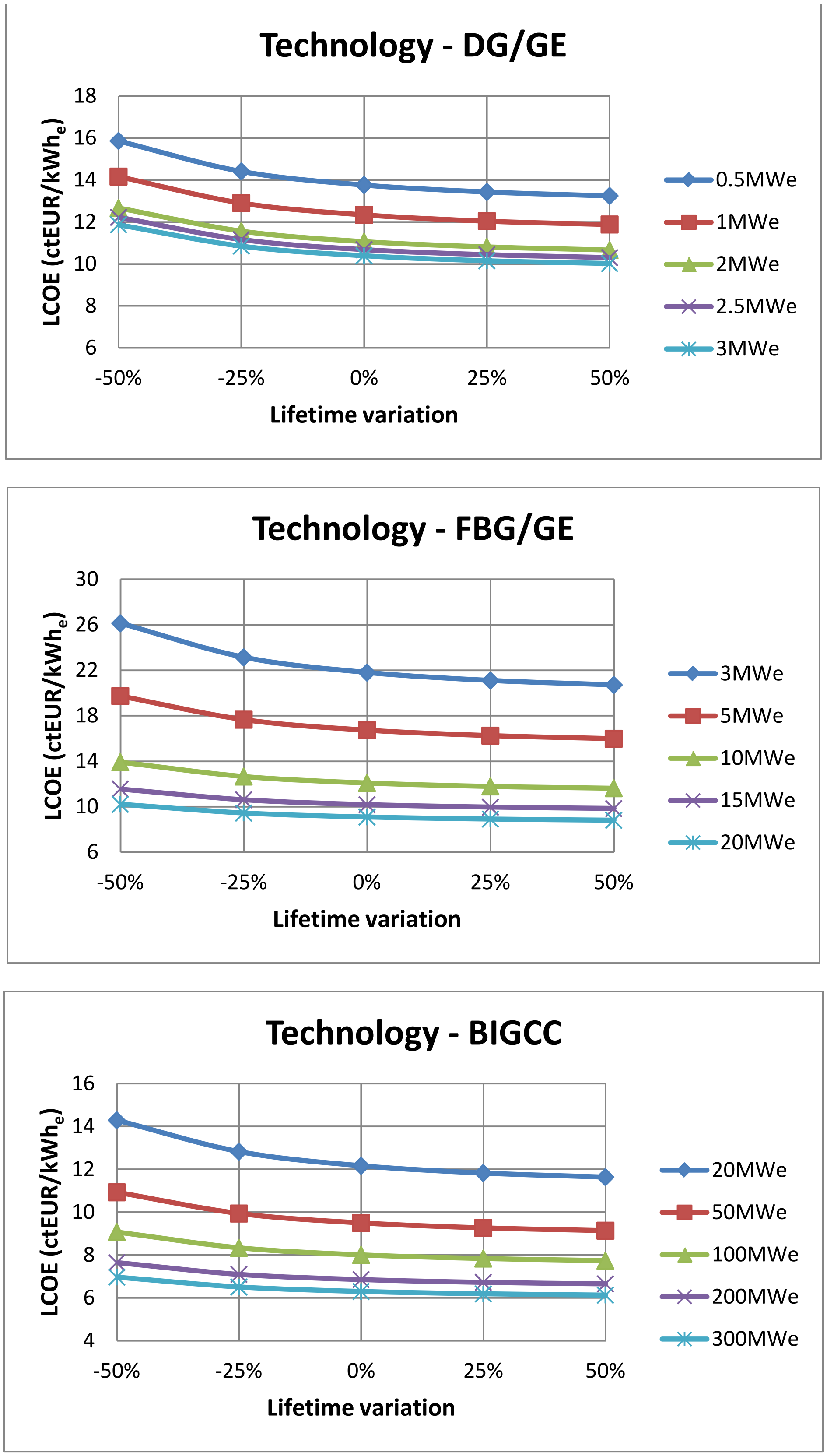


Figure 35 Sensitivity analysis regarding lifetime variation for selected technologies

4.5 Case studies

Two study cases are considered in this thesis in order to compare the feasibility of a technology for a specific small-scale and medium-scale range. The first study case compares DG/GE and FBG/GE technologies for a capacity of 3 MW_e. The second study case compares FBG/GE and BIGCC technologies for a capacity of 20 MW_e.

When the input parameters are considered same as Table 14 (base case) the performance results for the two study cases using the developed mathematical tool are as follows:

- DG/GE (3 MW_e)—Estimated Electrical Efficiency (33%); LCOE (10.39 ctEUR/kWh_e)
- FBG/GE (3 MW_e)—Estimated Electrical Efficiency (26%); LCOE (21.80 ctEUR/kWh_e)

- FBG/GE (20 MW_e)—Estimated Electrical Efficiency (33%); LCOE (9.09 ctEUR/kWh_e)
- BIGCC (20 MW_e)—Estimated Electrical Efficiency (36%); LCOE (12.17 ctEUR/kWh_e)

When the input parameters are considered same as Table 14 (base case) the total investments results for the two study cases using the developed mathematical tool are as follows:

- DG/GE (3 MW_e)—Total Invests 6.86 million EUR (Spec. Invests 2290 EUR/kW_e)
- FBG/GE (3 MW_e)—Total Invests 20.07 million EUR (Spec. Invests 6700 EUR/kW_e)

- FBG/GE (20 MW_e)—Total Invests 34.54 million EUR (Spec. Invests 1730 EUR/kW_e)
- BIGCC (20 MW_e)—Total Invests 65.29 million EUR (Spec. Invests 3265 EUR/kW_e)

Considering the above results, it can be depicted that for small-scale ranges DG/GE and for medium-scale ranges FBG/GE is the more competitive technology. For large-scale ranges only BIGCC technology is competitive. A comparison is made with LCOEs result to check the feasibility of the technologies more precisely with the variation of some important input parameters such as discount rate, fuel cost, and lifetime. In the following Figures 36 and 37 the LCOE results are shown for the two study cases. In both the study cases for the variation of discount rate and fuel cost the LCOE variation is positive. With the variation of plant lifetime the variation of LCOE is negative. Another observation is that the variation of LCOE for DG/GE (3 MW_e) and FBG/GE (20 MW_e) is rather reserved because this specified capacity is the highest feasible size for this type of biomass based power plants.

Finally, after the extensive study and calculation of LCOEs for the selected biomass gasification technologies it can be mentioned that the most important parameters for better economic performance are as follows:

- The size of the power plant
- The electrical efficiency of the selected technology
- LHV of biomass feedstock
- Total lifetime of the plant
- Rate of discount
- Biomass fuel cost

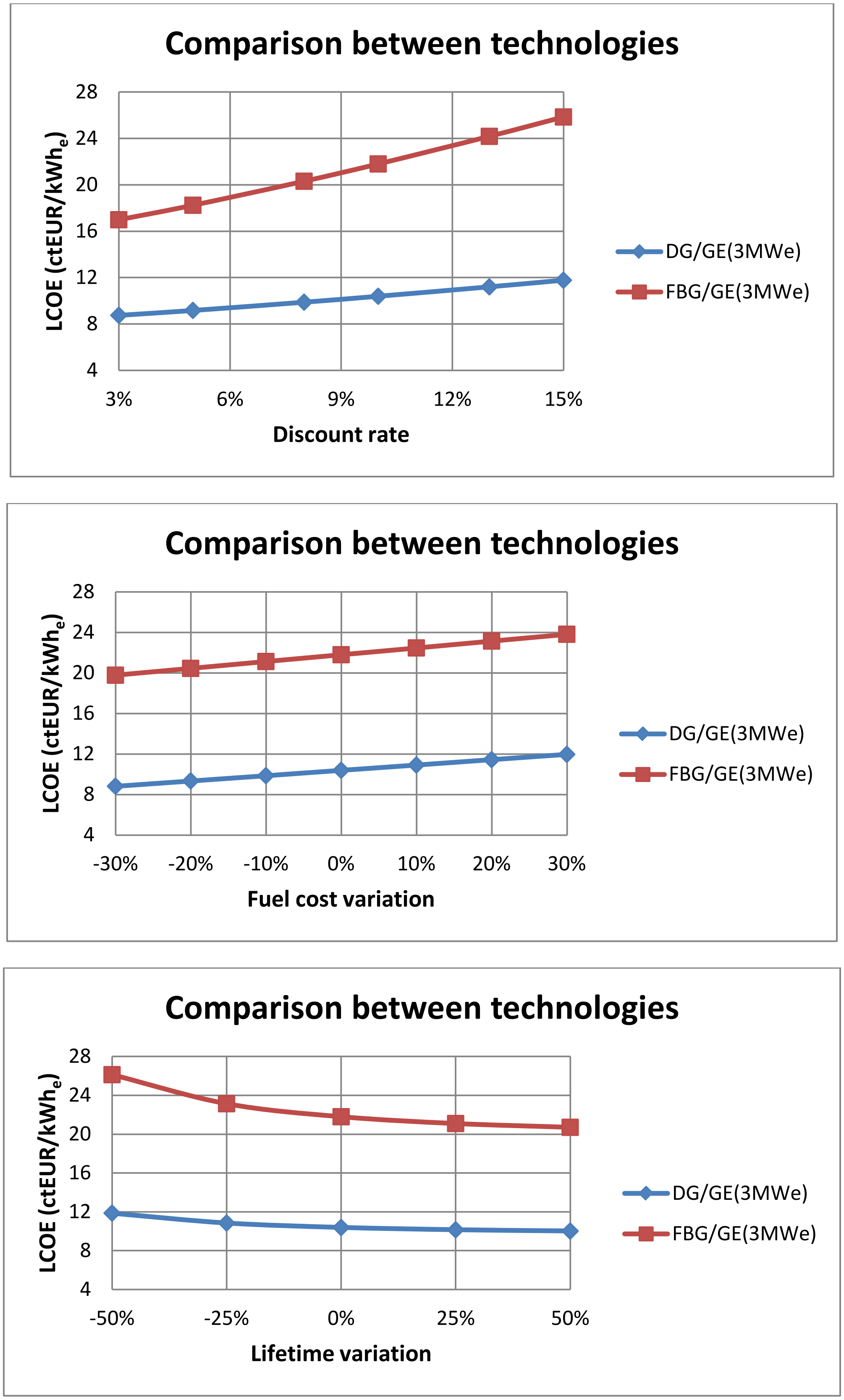


Figure 36 Comparison between technologies for first study case (small-scale)

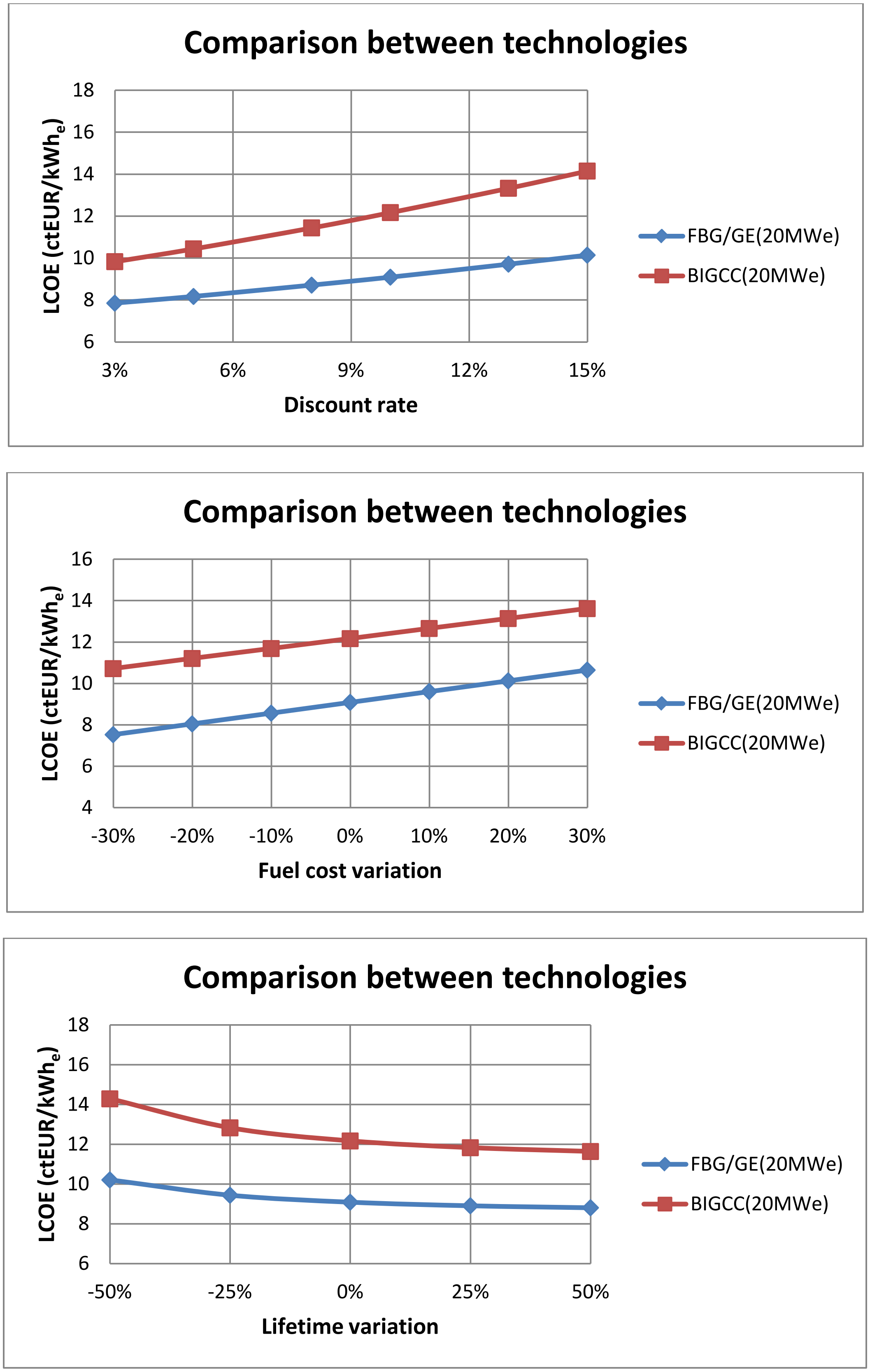


Figure 37 Comparison between technologies for second study case (medium-scale)

4.6 Summary on research questions

At the beginning of this thesis report in chapter 1 some research questions were outlined. All of these questions were addressed in previous sections. A brief summary follows:

In relation to the first question the most available commercial technologies for energy generation were characterized in this study. These are DG/GE, FBG/GE, and BIGCC.

To satisfy the second question an efficiency model is generated for each technology using the collected literature data of electrical efficiency of the selected technologies. These models are used in the mathematical tool for the estimation of total power production knowing the amount of available woody biomass beforehand.

The third question sought for the most important parameters for evaluating the economic performance of a biomass based gasification plant. These specific economic parameters are explained in details in chapter 3 and 4. Among these most important factors considered are discount rate, lifetime, and fuel cost. However, the impacts of these individual parameters are varying.

The following question asked for the approximate levelized costs of energy generation using the selected technologies. This question was addressed in this chapter in the section key findings. It was observed that LCOE of the selected technologies varies widely depending on the variation of the input parameters. In this case LCOE's were in the range of 6.30 ctEUR/kWh$_e$—27.15 ctEUR/kWh$_e$.

The final question asked for the most suitable technology among the options to set up a new plant with a specific scale range. It was noticed that for a specific size of the plant (i.e. small, medium, or big) not all of these technologies provide competitive results. Each technology follows a capacity range within which it gives the best possible outcome. For this reason it was found that for small-scale plants DG/GE, for medium-scale plants FBG/GE, and for large-scale plants BIGCC are the most competitive gasification technologies from techno-economic point of view.

Finally, during the study it was observed that the main decisive factors for estimating the economic performance of any biomass based energy conversion systems are the electrical efficiencies in conjunction with the specific investments of the specific technologies and these two factors are highly dependent on scale, in a way that efficiencies increase and specific investments decrease with up-scaling.

5. Conclusion

Three different process configurations for biomass gasification power production have been analyzed and assessed from technical and economic perspectives. The technical assessment focuses primarily on the operating principles and the electrical efficiencies of the selected technologies. The economic analysis was carried out based on the levelized costs of energy generation method.

The results show that the economic performance of a biomass based power plant largely depends on its size. The larger is the power plant in capacity; the better is the electrical efficiency, and the overall economic performance. It was noticed that, the two main parameters influencing the electricity production costs are the investments, and the price of the available biomass feedstock, i.e. fuel costs. Because of this, the competitive economic performance of a technology is highly dependent on individual plant site situations.

For the calculation of LCOE's of the selected technologies, some assumptions were made considering the input parameters. These assumed values are not fixed and may change anytime. For this reason, the obtained results should be considered as a qualitative approximation that may alter in real-time situation. Nevertheless, comparison of calculated LCOE results with existing literature data, in order to verify the consistency, shows only slight variations which may happen for several reasons.

The mathematical tool that was developed during this study may be considered as a useful means of analysis and comparison for the selected technologies to check which process configuration is best fit for a specific project.

5.1 Future works

Though this was an extensive study but there are some scopes of more research to be done.

First of all, an environmental assessment needs to be done to check some criteria as for example the global warming potential (GWP) and so on.

Secondly, the possibilities of co-generation (CHP) could be an area of research. This study primarily focused on electricity production potential overlooking the associated potential of heat production. But with the rising of electricity price and increasing demand for renewable energy, base load biomass-fired CHP plants will surely become more attractive option for clean energy production.

Future work may also consider the impact of the learning effects on the energy generation costs of biomass based plants.

Another important area of further research can involve the integration possibility of different renewable energy technologies. As mentioned earlier, biomass based conversion technologies can act as a back-up generation plant for intermittent renewable energy technologies such as wind and solar power. An optimization study could help to estimate the optimal size of a biomass-fired power plant which can serve as back-up for small to medium scale wind or solar farms. Important parameters needed to be considered for this scheme are amount of biomass feedstock and location of the proposed plant.

Finally, the mathematical tool that was developed for the calculation of LCOE can be improved further by considering more input parameters such as carbon costs.

5.2 Recommendation

As it is expected that, the price of fossil fuels will continue to increase in the near future due to several socio-economic reasons such as political unrest, biomass gasification could become a favorable technology for countries to limit their import and extensive use of fossil fuels, and to reduce the CO_2 emissions in a large extent. It is proven that among the biomass energy conversion pathways, gasification has a great potential because of its flexibility about feedstock, and different end products. However, the focus of its application is somehow reserved regarding electricity production compared to production of liquid transportation fuels, e.g. bio-fuels. Hence, the recommendation would be for the policy makers to start considering about biomass gasification as a prominent technology for sustainable electricity production.

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Glossary

Biomass – organic matter in trees, agricultural crops, and other living plant material.

Woody Biomass – trees, shrubs, bushes, or products derived from these kinds of woody plants that accumulate to an amount that is a hazard or disposal problem.

Gasification – a thermochemical conversion of organic solids and liquids into a producer or synthesis gas (syngas) under very controlled conditions of heat and strict control of air or oxygen.

Higher Heating Value (HHV) – it is defined as the total heat generated by the combustion of a fuel (Onovwiona, 2006). It is also called gross calorific value, or GCV (Obernberger, 1998).

Lower Heating Value (LHV) – the LHV is a thermodynamic property of a fuel conveying the energy content of that fuel, expressed in MJ/kg. It "is defined as the higher heating value of the fuel (HHV) less the energy required to vaporize the water produced during combustion" (Onovwiona, 2006). It is also called the net calorific value (NCV) (Obernberger, 1998).

Moisture Content – a measure of the amount of water in wood, expressed as a percentage.

Syngas – this is also known as producer gas, it is a gas obtained through gasification that can be used by boilers, internal combustion engines or gas turbines to produce heat and power in CHP systems after proper cleaning and conditioning (Dong, 2009).

Fixed bed technology - a fixed bed of feedstock is being gasified using a gasification medium, generally air at low velocity. Main types are downdraft and updraft gasifiers, which are mainly applied at smaller scales (Kirkels, 2011).

Fluidized bed technology - a small fraction of feedstock is added to a much larger fraction of bed material, which is then fluidized by a gasification medium (air, oxygen, steam) that flows through the bed at a high enough speed. Main types are the bubbling and the circulating fluidized bed, which are mainly applied for biomass at medium scales (Kirkels, 2011).

Fixed Costs – these are costs that do not depend on the rate of production. These include depreciation, insurance, rent, capital costs and maintenance costs (Crundwell, 2008).

Variable Costs – these are costs that fluctuate more or less according to the volume of total production. Some examples are costs of materials, fuel costs, labor and energy needed for production (Crundwell, 2008).

LCOE - the LCOE is the average price of electricity over the life time of the power plant to achieve a net present value (NPV) of zero (Orbaiz, 2014).

Total plant cost (TPC) - the TPC is the cost of building the plant. It includes not only the basic equipment costs, but also all process and support facilities, such as fuel handling and storage, waste treatment, construction of office spaces etc. (Orbaiz, 2014).

Fixed and variable operating and maintenance costs (FOM and VOM) - the fixed operation and maintenance costs (FOM) are related to the power capacity of the plant and are normally expressed in EUR/kW$_{yr}$ (Orbaiz, 2014). They include labor, personnel, equipment and overhead charges. Variable operation and maintenance costs (VOM) are usually related to the electricity production of the plant, and expressed in EUR/MWh (Orbaiz, 2014).

Annual overall power production - the overall power generation in kWh/yr is calculated as the plant's overall capacity times its capacity factor. The capacity factor is the percentage of time the power plant is generating at its rated capacity. Different power generating technologies have different capacity factors (Orbaiz, 2014).

Biomass emissions - biomass emissions can vary significantly based on fuel source and life-cycle emission assumptions. Conventionally, the release of carbon from biogenic sources is assumed to be balanced by the uptake of carbon when the feedstock is grown, resulting in zero net CO_2 emissions (Orbaiz, 2014).

Location of the plant - IEA and NEA (2010) consider the country-specific circumstances, such as market conditions and availability of biomass resources while estimating electricity production costs from biomass based power plants. According to the study done by Larsson et al. (2014), based on twelve different reports on electricity production costs for power generating technologies concluded that electricity production costs are country specific and sensitive to power plant location. Country specific circumstances have a big influence on estimation of different cost figures, which indicate the necessity to look at electricity production costs at the country level (Larsson, 2014).

Appendices

Appendix A List of companies involved in biomass gasification

[1] Selection of leading small scale (updraft and downdraft) biomass gasifier manufacturers and technologies used for energy generation in developed countries (Source: Kirkels, 2011; Juniper, 2007).

No.	Company Name	Country	Technology/Gasifier Type
1	Bioneer (now Foster Wheeler)	Finland	Updraft, heat
2	PRM Energy Systems Inc. (PRME)	USA	Updraft, heat/power
3	Babcock Wilcox Volund	Denmark	Updraft, heat and power
4	REL Waterwide technology	New Zealand	Downdraft, heat
5	Chiptec Wood Energy Systems	USA	Downdraft, heat
6	Fluidyne Gasification	New Zealand	Downdraft, power
7	Xylowatt	Belgium	Downdraft, power
8	AHT Pyrogas Vertriebs	Germany	Double zone, heat and power
9	COWI/DTU ‘Viking’ gasifier	Denmark	Multi stage, electricity
10	Biomass Engineering	UK	Downdraft
11	ITI Energy	UK	Fixed bed, proprietary design
12	Puhdas Energia Oy	Finland	Downdraft
13	Host	Netherlands	Fixed bed
14	Condens Oy – Novel gasifier	Finland	Fixed bed, counter current bottom

[2] List of the Leading suppliers of large scale and advanced biomass gasifiers is mentioned in Table below. It can be observed that for different market segments and feedstock availability different processes are leading (Source: Kirkels, 2011).

No.	Company Name	Country	Technology/Gasifier Type
1	Gas Technology Institute (GTI) - Renugas technology (Institute of Gas Technology (IGT))	USA	BFB, air/oxygen blown, pressurized
2	Repotec Umwelttechnik/Austrian Energy and Environment (Gussing CHP plant)	Austria	BFB, indirectly heated, steam blown (CFB air combustor)
3	Enerkem Technologies Inc. - BIOSYN technology	Canada	BFB, air/oxygen blown, pressurized
4	ThermoChem (Manufacturing and Technology Conversion International (MTCI))	USA	BFB, pulse enhanced, indirectly heated, steam blown, atmospheric (also) black liquor gasification
5	Envirotherm GmbH, part of Allied Environmental Solutions Inc. (Lurgi technology, BGL at Schwarze Pumpe)	Germany/USA	BGL fixed bed, slagging bottom, pressurized; CFB, atmospheric
6	Rentech Inc. - Rentech-Silvagas technology (Future Energy Resource Corporation (FERCO))	USA	CFB, indirectly heated, steam/air blown, atmospheric/low pressure
7	TPS Termiska Processor AB (ex Studsvik Energiteknik AB)	Sweden	CFB, air blown, atmospheric
8	Foster Wheeler (ex Ahlstrom)	USA/Finland	CFB, air blown, atmospheric/pressurized
9	Ebara - Twin Rec UEP Gasification technology	Japan	CFB, gas to slagging combustor, air blown, waste
10	Choren Industries GmbH - Carbo V technology (Deutsche Brennstoff Institut)	Germany	Entrained, involving pre-gasification or pyrolysis, air/oxygen blown, sewage sludge
11	Chemrec A.B. (ex Kvaerner Pulp & Paper)	Sweden	Entrained, air/oxygen blown, black liquor

12	Thermoselect S.A.	Switzerland	Pyrolyzer and entrained char gasifier, oxygen blown, waste
13	Siemens Fuel Gasification Technologies GmbH (Future Energy, BBP, NOEL-KRC, Deutsche Brennstof Institut)	Germany	Entrained, oxygen blown, pressurized
14	Energy Products of Idaho	USA	BFB

[3] Thermal gasification has been practiced for many years in several developed countries. In the Table below, a comprehensive list of thermal gasification commercial facilities is presented collecting data from Shafie, 2012.

Company Name	**Country**	**Raw material**	**Thermal output (MW_{th})**	**Electrical output (MW_{el})**	**Technology**
Andritz-Carbona	Denmark	Lignocelluloses, wood pellets	11	5.5	Fluidized bed reactor
Bubcock and Wilcox Volund	Denmark	Lignocelluloses, wood chips	3.5	1	Reactor updraft gasifier
Bubcock and Wilcox Volund	Japan	Lignocelluloses, wood chips	12	-	Updraft gasifier
Bubcock and Wilcox Volund	Japan	Lignocelluloses, wood chips	8	2	Updraft gasifier
Biomass Engineering Ltd	UK	Lignocelluloses, wood chips	-	1	Downdraft gasifier
Biomass Engineering Ltd	UK	Lignocelluloses, wood chips	-	0.25	Downdraft gasifier
FICFB	Austria	Lignocelluloses, wood chips	4.5	2	FICFB gasification
FICFB Oberwart	Austria	Lignocelluloses, wood chips	1-6	2.7	FICFB gasification
CHP Urban Neumarkt	Austria	Clean wood, biomass	0.58	0.240	Downdraft gasifier
CHP Urban Sulzbach-Laufen	Germany	Waste wood, biomass	0.28	0.13	Downdraft gasifier
CHP Heatpipie Reformer	Germany	Lignocelluloses, waste wood, clean wood	0.25	0.11	FB
CHP Urban Neunkirchen	Austria	Lignocelluloses, waste wood, clean wood	0.62	0.3	Downdraft gasifier
CHP Pyroforce Nidwalden	Switzerland	Lignocelluloses, dried chips	1.2	2x0.69	Downdraft pyroforce gasifier
CHP Wila	Switzerland	Lignocelluloses, dried chips	0.45	0.35	Downdraft woodpower gasifier

Appendix B Comparison between different technologies

[1] Comparison of Combustion, Gasification and Pyrolysis (Source: Roos, 2010)

Characteristics	Combustion	Gasification	Pyrolysis
Oxidizing agent	Greater than stoichiometric supply of oxygen*	Less than stoichiometric oxygen* or steam as the oxidizing agent	Absence of oxygen or steam
Typical temperature range with biomass fuels	800-1200^{0}C	800-1200^{0}C	350-600^{0}C
Principle products	Heat	Heat and combustible gas	Heat, combustible liquid and combustible gas
Principle components of gas	CO_2 and H_2O	CO and H_2	CO and H_2

*(In stoichiometric combustion, air supply is the theoretical quantity necessary to completely oxidize the fuel)

[2] Developments in gasification for both biomass and coal are summarized in Table below (Source: Kirkels, 2011).

Characteristics	Coal gasification	Biomass gasification
Preferred technology	Entrained flow	Updraft (small, mainly heat) Downdraft (small, mainly power) Circulating fluidized bed (large) Entrained flow (large, fuels and chemicals)
Main applications	Fischer Tropsch (South Africa) IGCC power Poly-generation in refineries e.g. China (ammonia, methanol)	Heat Combined heat and power (CHP) Co-combustion IGCC (research) Fuels and chemicals (research) Decentralized rural electrification in developing countries Waste management
Scale	100–1000’s MW_{th}	0.05–100’s MW_{th}
Dominant suppliers	Lurgi, GE, Shell	Multiple
Dominant countries	USA, Germany, China	USA, Finland, Sweden, Germany, Austria; Japan (waste); China, India (small scale)

Appendix C Efficiency data of selected gasification technologies

Efficiency data of technology DG/GE (References for Figure 22)

Data No.	Scale Thermal Input [MW_{th}]	Electrical Efficiency	Reference
1	0.07	0.25	Ahrenfeldt, 2013 p.1416
2	0.245	0.16	Margaritis, 2012 p.857
3	0.6	0.25	Juniper., 2007 p.101
4	0.8	0.25	Juniper., 2007 p.57
5	1.5	0.35	Ahrenfeldt, 2013 p.1416
6	2	0.25	Hofbauer, 2004 p.227
7	2.064	0.26	Obernberger, 2008 p.4
8	2.182	0.28	Obernberger, 2008 p.4
9	3	0.30	Dornburg, 2001 p.94

Efficiency data of technology DG/GE (References for Figure 23)

Data No.	Scale Electrical Output [MW_{el}]	Electrical Efficiency	Reference
1	0.01	0.15	Hollingdale, 2006 p.8
2	0.0131	0.21	Bocci, 2014 p.253
3	0.0175	0.25	Ahrenfeldt, 2013 p.1416
4	0.03	0.20	Bocci, 2014 p.253
5	0.07	0.16	Margaritis, 2012 p.857
6	0.1	0.18	Bocci, 2014 p.253
7	0.1	0.25	Hollingdale, 2006 p.8
8	0.2	0.15	Zhou, 2012 p.54
9	0.2	0.25	Demirbas, 2009 p.1749
10	0.25	0.25	Juniper., 2007 p.57
11	0.3	0.25	Juniper., 2007 p.101
12	0.384	0.29	Accornero, 2012 p.4
13	0.47	0.24	Salomon, 2011 p.4457
14	0.54	0.26	Obernberger, 2008 p.4
15	0.6	0.28	Obernberger, 2008 p.4
16	0.6	0.28	Kalt, 2011 p.3680
17	1	0.30	Demirbas, 2009 p.1749
18	1.3	0.33	Juniper., 2007 p.87
19	1.7	0.35	Juniper., 2007 p.87
20	2.5	0.35	Juniper., 2007 p.93

Efficiency data of technology FBG/GE (References for Figure 24)

Data No.	Technology	Scale Thermal Input (MW_{th})	Electrical Efficiency	Reference
1	FBG-GE	7.2	0.25	Salomon, 2011 p.4457
2	FBG-BIG-GE	8	0.20	Difs, 2010 p.639
3	FICFB-FBG	8	0.25	Ahrenfeldt, 2013 p.1409
4	CFB-FBG	10	0.37	Granatstein, 2004 p.13
5	FBG-GE	13.405	0.34	Obernberger, 2008 p.4
6	CFB-FBG	18	0.32	Stahl, 1998 p.208
7	FICFB-FBG	20	0.35	Juniper., 2007 p.97
8	FBG-GE	29.4	0.23	Yassin, 2009 p.321
9	BFB-FBG	36	0.28	Salomon, 2011 p.4456

Efficiency data of technology FBG/GE (References for Figure 25)

Data No.	Technology	Scale Electrical Output (MW_{el})	Electrical Efficiency	Reference
1	CFB-FBG	1	0.18	Zhang, 2013 p.183
2	CFB-FBG	1.2	0.20	Zhou, 2012 p.55
3	FBG-GE	1.8	0.25	Salomon, 2011 p.4457
4	FICFB-FBG	2	0.25	Ahrenfeldt, 2013 p.1409
5	FBG-GE	4.5	0.34	Obernberger, 2008 p.4
6	CFB-FBG	4.5	0.37	Granatstein, 2004 p.13
7	FBG-GE	5	0.34	Kalt, 2011 p.3680
8	CFB-FBG	5.5	0.28	Zhang, 2013 p.183
9	CFB-FBG	6	0.32	Stahl, 1998 p.208
10	FBG-GE	6.8	0.23	Yassin, 2009 p.321
11	FBG	8	0.28	Hollingdale, 2006 p.8
12	BFB-FBG	10	0.28	Salomon, 2011 p.4456
13	FBG	10	0.35	Hollingdale, 2006 p.9
14	BFB-FBG	11.7	0.28	Salomon, 2011 p.4456
15	CFB-FBG	14	0.32	Salomon, 2011 p.4456
16	FBG-GE	14.6	0.25	Yassin, 2009 p.321
17	BFB-FBG	14.7	0.31	Salomon, 2011 p.4457

Efficiency data of technology BIGCC (References for Figure 26)

Data No.	Technology	Scale Thermal Input (MW_{th})	Electrical Efficiency	Reference
1	BIGCC	12	0.4	Borjesson, 2010 p.173
2	BIGCC	18.5	0.3	Salomon, 2011 p.4456
3	BIGCC	20	0.43	Difs, 2010 p.639
4	BIGCC	31	0.42	Borjesson, 2010 p.173
5	BIGCC	47.1	0.38	Klimantos, 2009 p.712
6	BIGCC	48	0.31	Salomon, 2011 p.4457
7	BIGCC	50	0.32	Salomon, 2011 p.4456
8	BIGCC	60	0.34	Gustavsson, 2003 p.1414
9	BIGCC	60	0.43	Uddin, 2007 p.1010
10	BIGCC	60	0.43	Joelsson, 2009 p.129
11	BIGCC	60	0.43	Borjesson, 2010 p.173
12	BIGCC	65	0.31	Granatstein, 2004 p.13
13	BIGCC	80	0.43	Gustavsson, 2011 p.41
14	BIGCC	100	0.43	Uddin, 2007 p.1010
15	BIGCC	100	0.43	Borjesson, 2010 p.173
16	BIGCC	109	0.43	Truong, 2013 p.625
17	BIGCC	114	0.42	Klimantos, 2009 p.712
18	BIGCC	130	0.43	Borjesson, 2010 p.173
19	BIGCC	160.3	0.44	Klimantos, 2009 p.712
20	BIGCC	166.6	0.40	Klimantos, 2009 p.712
21	BIGCC	200	0.43	Uddin, 2007 p.1010
22	BIGCC	300	0.43	Difs, 2010 p.639
23	BIGCC	400	0.43	Wetterlund, 2010 p.2917

Efficiency data of technology BIGCC (References for Figure 27)

Data No.	Technology	Scale Electrical Output (MW_{el})	Electrical Efficiency	Reference
1	BIGCC	5.5	0.30	Zhou, 2012 p.55
2	A-BIGCC	6	0.33	Marbe, 2004 p.1126
3	A-BIGCC	8	0.29	Brown, 2009 p.2141
4	P-BIGCC	8	0.38	Marbe, 2004 p.1126
5	BIGCC	10	0.30	Demirbas, 2009 p.1749
6	BIGCC	10	0.40	Borjesson, 2010 p.173
7	BIGCC	15	0.30	Juniper., 2007 p.77
8	P-BIGCC	17.9	0.38	Klimantos, 2009 p.712
9	BIGCC	25.6	0.36	Faaij, 1997 p.392
10	BIGCC	26.8	0.39	Faaij, 1997 p.392
11	BIGCC	29	0.40	Faaij, 1997 p.392

12	BIGCC	30	0.40	Demirbas, 2009 p.1749
13	BIGCC	30	0.42	Borjesson, 2010 p.173
14	A-BIGCC	32	0.40	Brown, 2009 p.2141
15	BIGCC	45.5	0.37	Dowaki, 2005 p.57
16	BIGCC	46.3	0.38	Dowaki, 2005 p.57
17	BIGCC	47.1	0.39	Dowaki, 2005 p.57
18	P-BIGCC	48	0.42	Klimantos, 2009 p.712
19	BIGCC	50	0.29	Craig, 1996 p.32
20	BIGCC	50	0.43	Kalt, 2011 p.3680
21	BIGCC	51	0.41	Dowaki, 2005 p.57
22	BIGCC	55.5	0.36	Craig, 1996 p.21
23	BIGCC	56	0.36	Craig, 1996 p.32
24	BIGCC	60	0.34	Gustavsson, 2003 p.1414
25	BIGCC	60	0.43	Uddin, 2007 p.1010
26	BIGCC	60	0.43	Borjesson, 2010 p.173
27	BIGCC	60	0.43	Joelsson, 2009 p.129
28	BIGCC	64	0.29	Craig, 1996 p.32
29	P-BIGCC	66.7	0.40	Klimantos, 2009 p.712
30	P-BIGCC	70.6	0.44	Klimantos, 2009 p.712
31	A-BIGCC	77	0.33	Marbe, 2004 p.1126
32	BIGCC	100	0.43	Borjesson, 2010 p.173
33	BIGCC	100	0.43	Uddin, 2007 p.1010
34	BIGCC	100	0.47	Joelsson, 2009 p.129
35	BIGCC	100	0.47	Gustavsson, 2011 p.41
36	BIGCC	100	0.47	Truong, 2013 p.626
37	P-BIGCC	104	0.38	Marbe, 2004 p.1126
38	BIGCC	105.4	0.38	Craig, 1996 p.21
39	BIGCC	122	0.35	Craig, 1996 p.21
40	BIGCC	130	0.43	Borjesson, 2010 p.173
41	BIGCC	131.7	0.40	Craig, 1996 p.21
42	BIGCC	149	0.34	Rhodes, 2005 p.446
43	BIGCC	200	0.43	Uddin, 2007 p.1010

Appendix D Specific investments data of selected gasification technologies

Specific investments data for technology DG/GE (References for Figure 28)

Original Data Collected from Literature						Calculated value of SI for the base year 2013
Data No.	**Reference**	**Technology**	**Scale Electrical Output (MW$_{el}$)**	**Spec. Investment (SI)**	**Base Year [Data]**	Spec. Investment (SI) [EUR/kW$_{el}$]
1	Juniper., 2007 p.58	DDG-GE	0.05	3930 EUR/ kW (el)	2007	4260
2	Juniper., 2007 p.58	DDG-GE	0.1	3785 EUR/ kW (el)	2007	4103
3	Juniper., 2007 p.58	DDG-GE	0.15	3600 EUR/ kW (el)	2007	3903
4	Balat, 2009 p.3162	DDG-GE	0.2	4000 USD/ kW (el)	2007	3209
5	Juniper., 2007 p.58	DDG-GE	0.25	3500 EUR/ kW (el)	2007	3794
6	Juniper., 2007 p.58	DDG-GE	0.5	2900 EUR/ kW (el)	2007	3144
7	Obernberger, 2008 p.6	DDG-GE	0.54	4928 EUR/ kW (el)	2008	4878
8	Obernberger, 2008 p.6	DDG-GE	0.6	5687 EUR/ kW (el)	2008	5629
9	Juniper., 2007 p.45	DDG-GE	1	2667 GBP/ kW (el)	2007	3585
10	Balat, 2009 p.3162	DDG-GE	1	3000 USD/ kW (el)	2007	2407
11	Salomon, 2011 p.4458	DDG-GE	2	1300 EUR/ kW (el)	2011	1264
12	Juniper., 2007 p.62	DDG-GE	2	1900 GBP/ kW (el)	2007	2554

Specific investments data for technology FBG/GE (References for Figure 29)

Original Data Collected from Literature						Calculated value of SI for the base year 2013
Data No.	Reference	Technology	Scale Electrical Output (MW_{el})	Spec. Investment (SI)	Base Year [Data]	Spec. Investment (SI) [EUR/kW_{el}]
1	Difs, 2010 p.643	CFB-FBG	1.8	8300 EUR/ kW (el)	2009	9057
2	Obernberger, 2008 p.6	FBG-GE	4.5	4397 EUR/ kW (el)	2008	4352
3	Kalt, 2011 p.3680	FBG-GE	5	5159 EUR/ kW (el)	2009	5630
4	Brown, 2009 p.2146	FBG-GE	8.269	3590 EUR/ kW (el)	2004	4603
5	Brown, 2009 p.2146	FBG-GE	8.685	3030 EUR/ kW (el)	2004	3885
6	Juniper., 2007 p.100	CFB-FBG	10	1500 USD/ kW (el)	2001	1604
7	Juniper., 2007 p.78	FBG-GE	15	2000 EUR/ kW (el)	2007	2168

Specific investments data for technology BIGCC (References for Figure 30)

Original Data Collected from Literature						Calculated value of SI for the base year 2013
Data No.	Reference	Technology	Scale Electrical Output (MW_{el})	Spec. Investment (SI)	Base Year [Data]	Spec. Investment (SI) [EUR/kW_{el}]
1	Bridgwater, 1995 p.634	P-BIGCC	6	6000 USD/ kW (el)	1994	6637
2	Balat, 2009 p.3162	BIGCC	10	5500 USD/ kW (el)	2007	4412
3	Borjesson, 2010 p.173	BIGCC-CHP	10	2600 EUR/ kW (el)	2004	3334
4	Bridgwater, 1995 p.634	A-BIGCC	16	3200 USD/ kW (el)	1994	3540
5	Klimantos, 2009 p.712	BIGCC-CHP	17.9	3870 EUR/ kW (el)	2008	3831
6	Balat, 2009 p.3162	BIGCC	30	2500 USD/ kW (el)	2007	2006
7	Borjesson, 2010 p.173	BIGCC-CHP	30	1900 EUR/ kW (el)	2004	2436
8	Klimantos, 2009 p.712	BIGCC-CHP	48	2700 EUR/ kW (el)	2008	2673
9	Wetterlund, 2010 p.2917	BIGCC-CHP	50	2300 EUR/ kW (el)	2009	2510

10	Kalt, 2011 p.3680	BIGCC-CHP	50	2300 EUR/ kW (el)	2009	2510
11	Marbe, 2004 p.1127	A-BIGCC	50	13000 SEK/ kW (el)	2002	2059
12	Difs, 2010 p.643	BIGCC-CHP	50	2300 EUR/ kW (el)	2009	2510
13	Bridgwater, 1995 p.634	P-BIGCC	55	4200 USD/ kW (el)	1994	4646
14	Joelsson, 2009 p.129	BIGCC-CHP	60	1542 EUR/ kW (el)	2006	1758
15	Borjesson, 2010 p.173	BIGCC-CHP	60	1500 EUR/ kW (el)	2004	1923
16	Gustavsson, 2003 p.1414	BIGCC-CHP	60	1600 USD/ kW (el)	2002	1705
17	Uddin, 2007 p.1010	BIGCC-CHP	60	1805 USD/ kW (el)	2006	1523
18	Marbe, 2004 p.1127	P-BIGCC	60	11000 SEK/ kW (el)	2002	1742
19	Klimantos, 2009 p.712	BIGCC-CHP	66.7	2383 EUR/ kW (el)	2008	2359
20	Klimantos, 2009 p.712	BIGCC-CHP	70.6	2100 EUR/ kW (el)	2008	2079
21	Borjesson, 2010 p.173	BIGCC-CHP	100	1300 EUR/ kW (el)	2004	1667
22	Uddin, 2007 p.1010	BIGCC-CHP	100	1730 USD/ kW (el)	2006	1460
23	Truong, 2013 p.626	BIGCC-Power	100	1680 EUR/ kW (el)	2007	1821
24	Gustavsson, 2011 p.41	BIGCC-Power	100	1680 EUR/ kW (el)	2007	1821
25	Joelsson, 2009 p.129	BIGCC-Power	100	1186 EUR/ kW (el)	2006	1352
26	Gustavsson, 2003 p.1414	BIGCC	100	1300 USD/ kW (el)	2002	1385
27	Borjesson, 2010 p.173	BIGCC-CHP	130	1200 EUR/ kW (el)	2004	1539
28	Rhodes, 2005 p.446	BIGCC-CHP	149	1250 USD/ kW (el)	2000	1337
29	Uddin, 2007 p.1010	BIGCC-CHP	200	1510 USD/ kW (el)	2006	1274
30	Gustavsson, 2003 p.1414	BIGCC	250	1080 USD/ kW (el)	2002	1151