Advances and Trends in Woody Biomass Gasification

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November 2014

Abstract

Renewable energy technologies can assist countries meet their policy demands for secure, reliable and affordable energy through broadening electricity access and stimulating development in both the urban and rural territories. Among the renewable energy sources biomass is a versatile resource which can play a major role for the development of a 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 namely fixed and fluidized bed gasification were extensively investigated. A 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 of this study includes the selection of a suitable technology for a biomass based plant at a specific capacity range from both technical and economic point of view. It was observed that for small-scale plants the most efficient technology is the internal combustion engine (ICE) coupled to a gasification unit. For medium to large scale plants gas or steam turbines perform better. Most favorable technology with respect to both economic and energy provisions are BIGCC (Biomass Integrated Gasification Combined Cycle) plants. Important results include for DG/GE (Downdraft Gasification/Gas Engine) plants with scale range 0.01-3 MW_e the LCOE range is 10.39-25.46 ctEUR/kWh_e, for FBG/GE (Fluidized Bed Gasification/Gas Engine) 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.

Keywords:
Biomass, Fixed bed gasification, Fluidized bed gasification, BIGCC, Electrical efficiency, Levelized costs of energy generation (LCOE).

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).

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 feedstock to a wide variety of applications, as shown in Figure 1 (Kirkels, 2011).

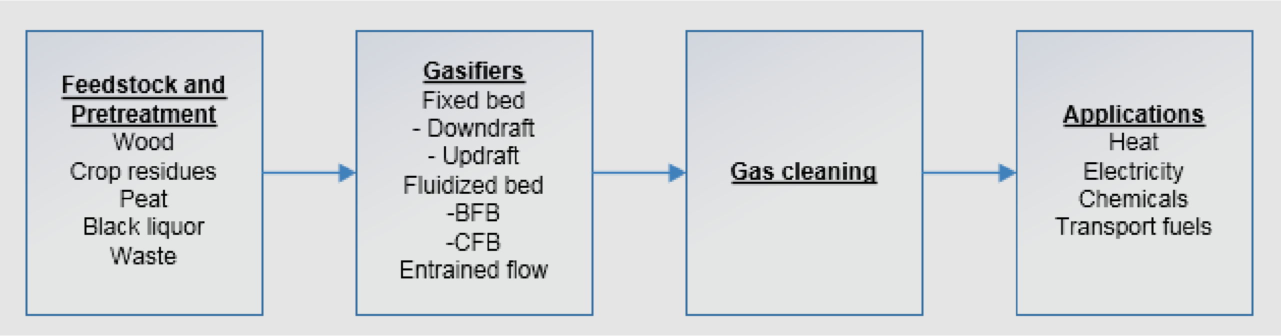


Figure 1 Flexibility of gasification technology in advanced applications (Source: Kirkels, 2011)

2. Literature Review

2.1 Present 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 is widespread. 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). 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 2 and Figure 3. In 2005, the total capacity of biomass power generation was 15.7 GW_e including all the member states. With a capacity 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 2, 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 3.

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 1.

Table 1 Leading countries engaged in the gasification of different biomass feedstock (Source: Kirkels, 2011)

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

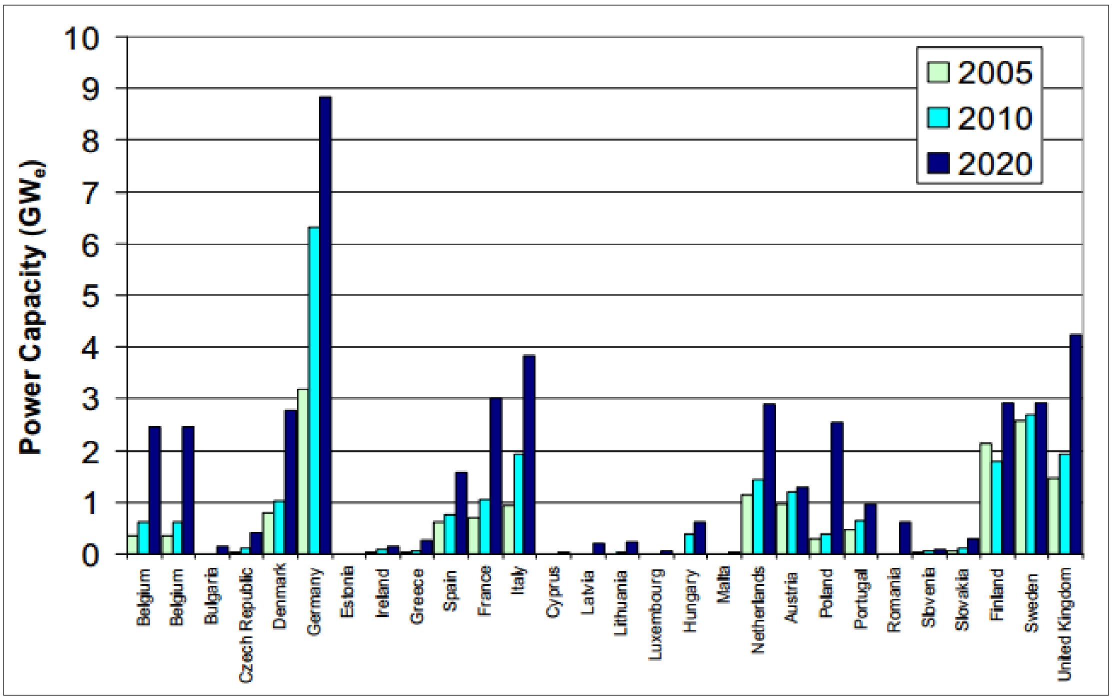


Figure 2 Biomass power production capacity (GW_e) in 2005, 2010 and 2020 in accordance with EU National Renewable Energy Action Plans (Source: EURELECTRIC, 2011)

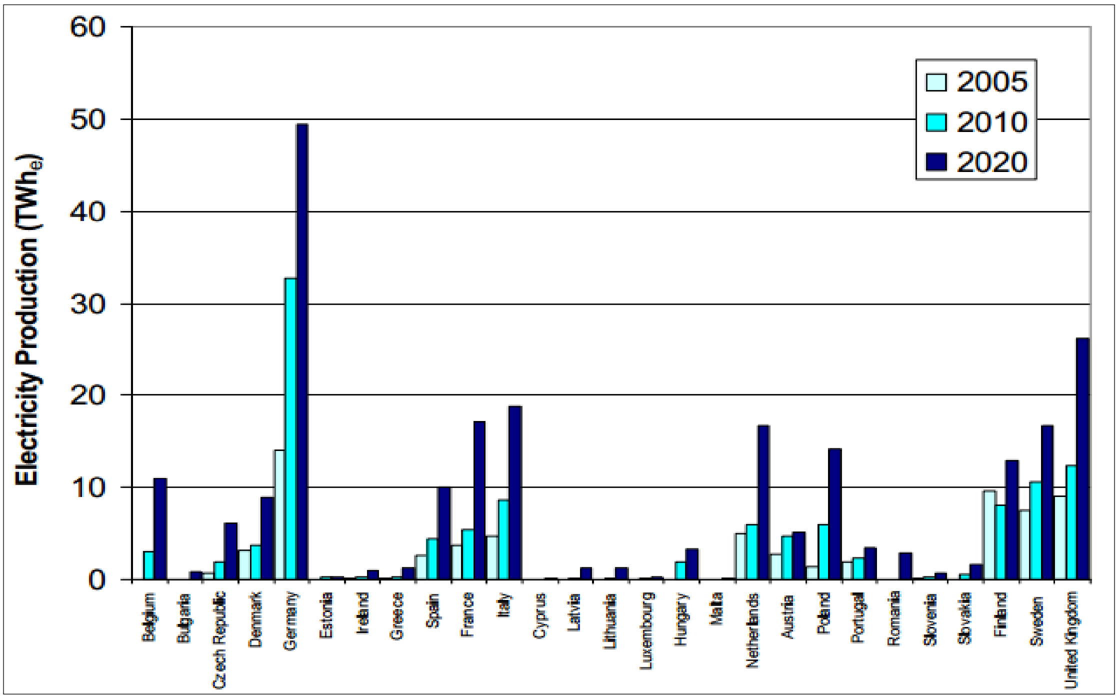


Figure 3 Biomass electricity production (TWh_e) in 2005, 2010 and 2020 in accordance with EU National Renewable Energy Action Plans (Source: EURELECTRIC, 2011)

2.2 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 4.

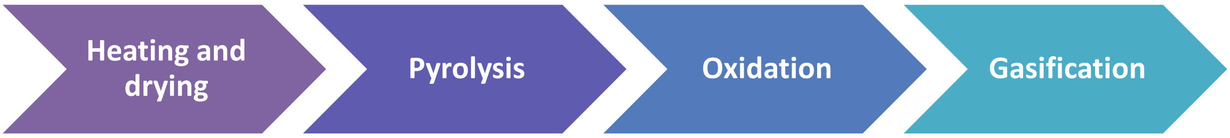


Figure 4 Gasification process steps (Source: Ruiz, 2013)

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).

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

2.3 The 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). 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 5.

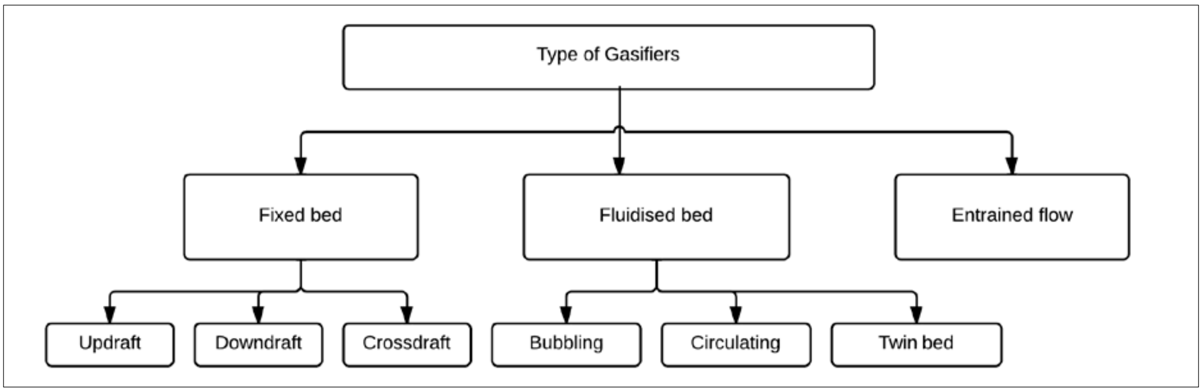


Figure 5 Classification of gasifiers (Source: Basu, 2010)

The summary of the notable features and comparative evaluation of fixed bed, fluidized bed, and entrained flow gasifiers is presented in Table 2.

Table 2 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%

2.4 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 3, a brief summary of secondary technologies that could be useful in combination with biomass gasifiers are discussed.

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).

Table 3 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

3. 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 appropriate 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.

Based on the capability to produce electricity with greater efficiency, three technologies have been selected for extensive evaluation. These are as follows (Dornburg, 2001):

- ➢ 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 (A-BIGCC/P-BIGCC)

3.1 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.

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 1 (Larsson, 2014).

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

Here, $\boldsymbol{I_t}$ is the investment spending in the year t, $\boldsymbol{O\&M_t}$ is the cost of operation & maintenance in the year t, $\boldsymbol{F_t}$ is the fuel spending in the year t, $\boldsymbol{S_t}$ is the supplementary expenses in the year t, $\boldsymbol{E_t}$ 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 6.

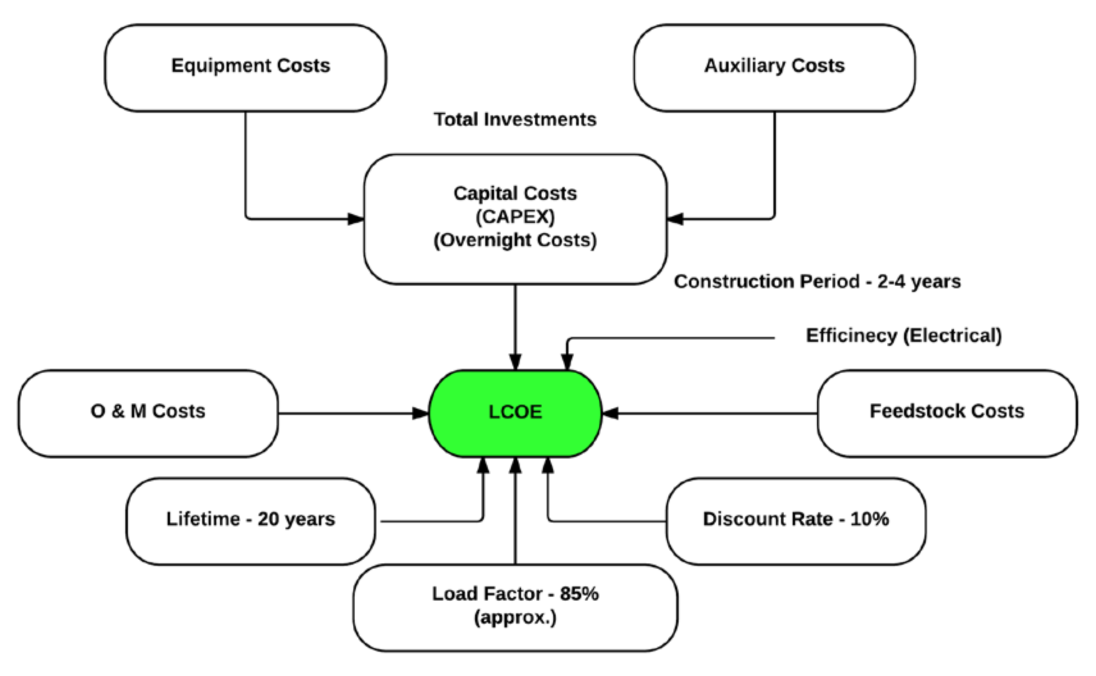


Figure 6 LCOE framework for biomass power generation (Source: Adapted from IRENA, 2012)

4. Results and Key findings

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.

4.1 Electrical efficiency models

The electrical efficiency of the selected biomass gasification technologies are modeled using regression technique on the gathered data. All the electrical efficiency data collected from different sources for the selected technologies are presented in the following plots in Figure 7 with respect to power plant capacity. 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%.

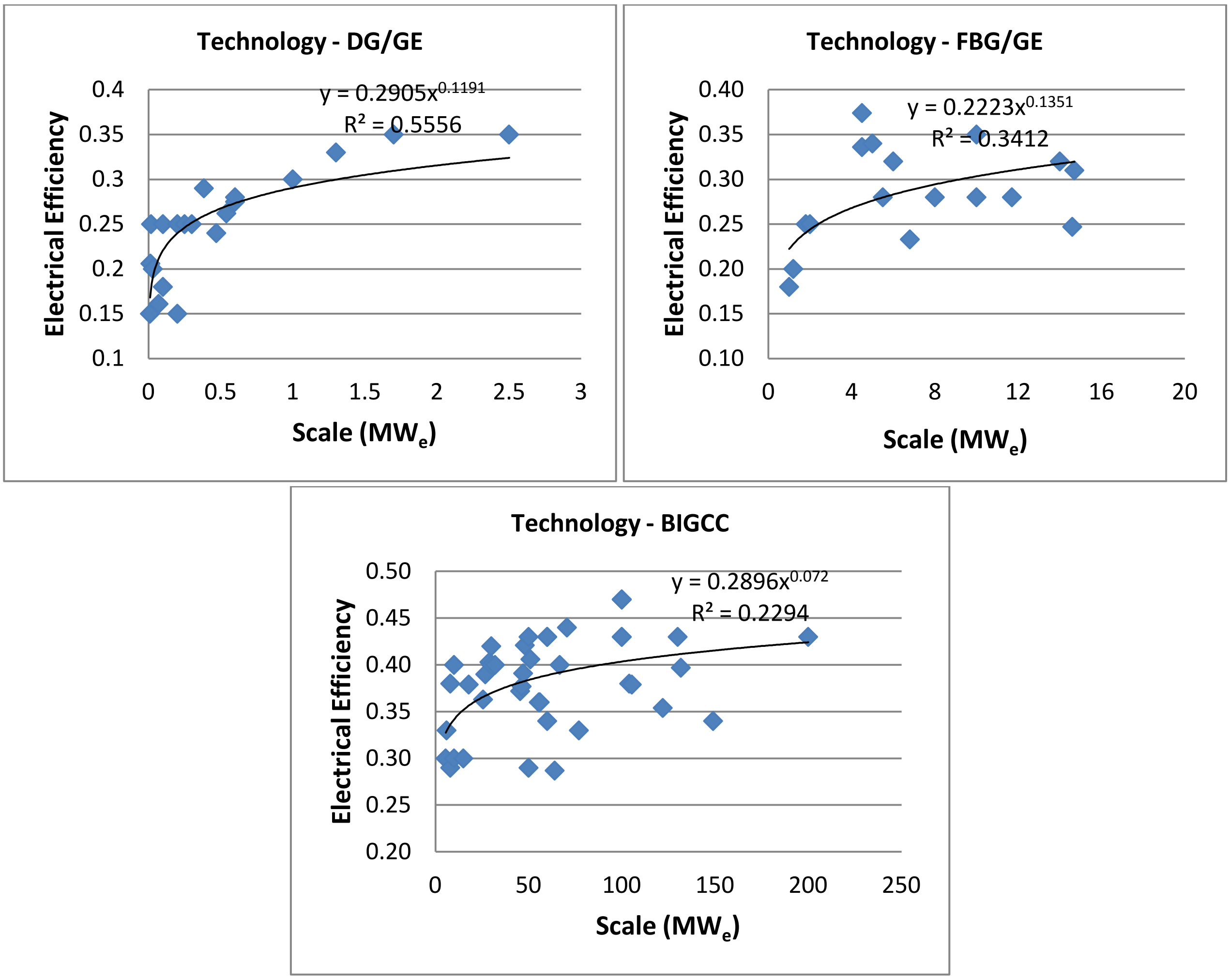
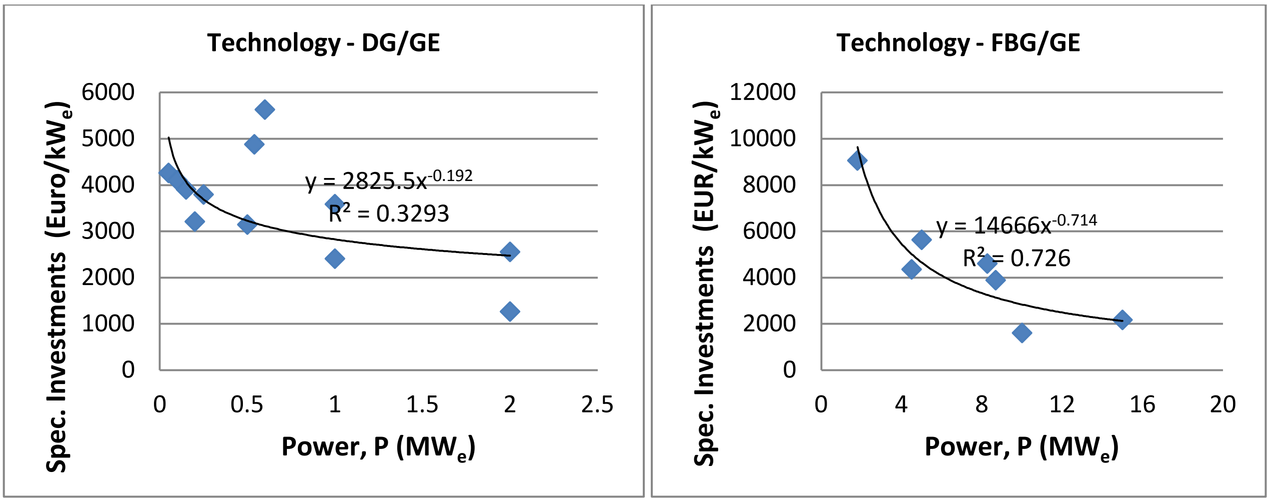


Figure 7 Electrical efficiencies of selected plants along output power scale

4.2 Specific investments models

The specific investments of the selected biomass gasification technologies are modeled using regression technique on the gathered data. All the specific investments data collected from different sources for the selected technologies are presented in the following plots in Figure 8 with respect to power plant capacity. 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 appropriate technology.



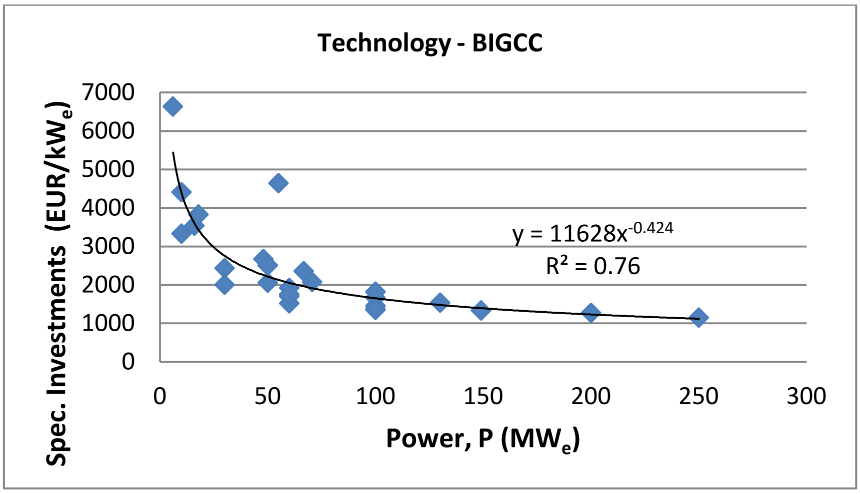


Figure 8 Specific invests for selected plants along output power scale

4.3 Key findings

The main results of the study and calculations are summarized in Table 4.

Table 4 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 gasification technologies is presented in the following Figure 9. 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)

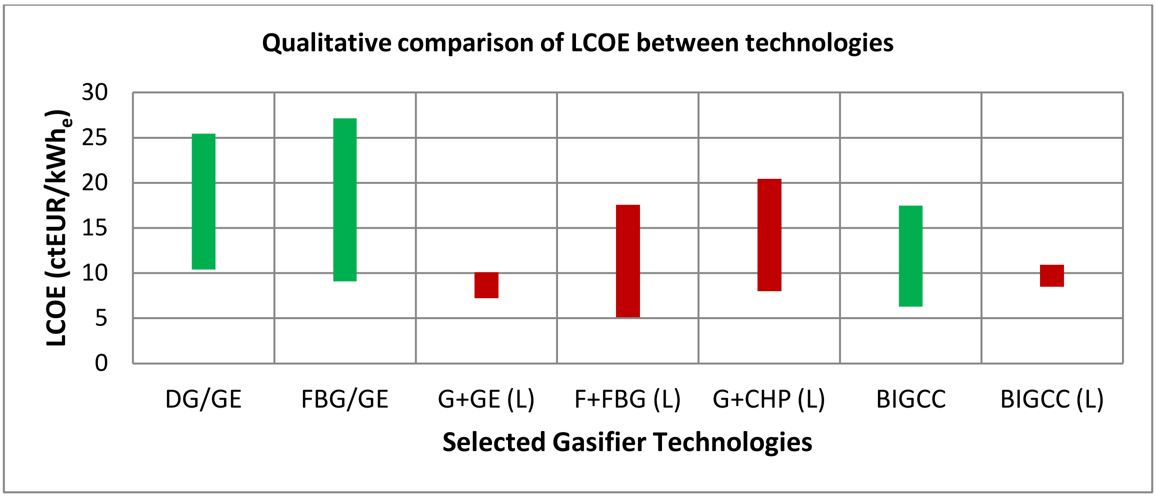


Figure 9 Comparison of LCOE range for biomass gasification based plants

4.4 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. 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 $ctEUR/kWh_e$)

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. 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

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.

Finally, 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 considered 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 fuel, e.g. bio-fuels. The recommendation would be for the policy makers to start considering about biomass gasification as a prominent technology for sustainable electricity production.

References

Arena, U. (2012). Process and technological aspects of municipal solid waste gasification: a review. *Waste Management , 32*, 625-639.

Asadullah, M. (2014). Barriers of commercial power generation using biomass gasification gas: A review. *Renewable and Sustainable Energy Reviews , 29*, 201-215.

Balat, M., Balat, M., Kirtay, E., & Balat, H. (2009). Main routes for the thermo-conversion of biomass into fuels and chemicals. Part 2: Gasification systems. *Energy Conversion and Management , 50*, 3158-3168.

Basu, P. (2010). Gasification theory and modeling of gasifiers. In *Biomass Gasification Design Handbook* (pp. 117-165). Boston: Academic Press.

Bauen, A., Berndes, G., Junginger, M., Londo, M., Vuille, F., Ball, R., et al. (2009). *Bioenergy-A Sustainable and Reliable Energy Source.* Paris: IEA Bioenergy.

Bridgwater, A. V. (1995). The technical and economic feasibility of biomass gasification for power generation. *Fuel , 74* (5), 631-653.

Bridgwater, A. V., Toft, A. J., & Brammer, J. G. (2002). A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. *Renewable & Sustainable Energy Reviews , 6*, 181-248.

Buragohain, B., Mahanta, P., & Moholkar, V. S. (2010). Biomass gasification for decentralized power generation: The Indian perspective. *Renewable and Sustainable Energy Reviews , 14*, 73-92.

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., et al. (2011). *Bioenergy. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation.* Cambridge: Cambridge University Press, UK.

Coronado, C. R., Yoshioka, J. T., & Silveira, J. L. (2011). Electricity, hot water and cold water production from biomass. Energetic and economical analysis of the compact system of co-generation run with woodgas from a small downdraft gasifier. *Renewable Energy , 36*, 1861-1868.

Demirbas, M. F., Balat, M., & Balat, H. (2009). Potential contribution of biomass to the sustainable energy development. *Energy Conversion and Management , 50*, 1746-1760.

Difs, K., Wetterlund, E., Trygg, L., & Soderstrom, M. (2010). Biomass gasification opportunities in a district heating system. *Biomass & Bioenergy , 34*, 637-651.

Dornburg, V., & Faaij, A. P. (2001). Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. *Biomass & Bioenergy , 21*, 91-108.

EURELECTRIC. (2011). *Biomass 2020: Opportunities, Challenges and Solutions.* EURELECTRIC Renewables Action Plan (RESAP).

Evans, A., Strezov, V., & Evans, T. J. (2010). Sustainability considerations for electricity generation from biomass. *Renewable and Sustainable Energy Reviews , 14*, 1419-1427.

Fiorese, G., Catenacci, M., Bosetti, V., & Verdolini, E. (2014). The power of biomass: Experts disclose the potential for success of bioenergy technologies. *Energy Policy , 65*, 94-114.

Hook, M., & Tang, X. (2013). Depletion of fossil fuels and anthropogenic climate change—A review. *Energy Policy , 52*, 797-809.

Huda, A. N., Mekhilef, S., & Ahsan, A. (2014). Biomass energy in Bangladesh: Current status and prospects. *Renewable & Sustainable Energy Reviews , 30*, 504-517.

IEA, & NEA. (2010). *Projected Costs of Generating Electricity.* OECD. Paris: International Energy Agency; Nuclear Energy Agency.

International Energy Agency (IEA). (2006). *World Energy Outlook 2006.* Paris: IEA.

Invernizzi, C., Iora, P., & Silva, P. (2007). Bottoming micro-Rankine cycles for micro-gas turbines. *Applied Thermal Engineering , 27*, 100-110.

IRENA. (2012). *Renewable Energy Technologies: Cost Analysis Series; Biomass for Power Generation.* UAE: International Renewable Energy Agency.

Kaygusuz, K. (2009). Biomass as a Renewable Energy Source for Sustainable Fuels, Energy Sources, Part A:Recovery, Utilization, and Environmental Effects. *31:6*, 535-545.

Kirkels, A. F., & Verbong, G. P. (2011). Biomass gasification: Still promising? A 30-year global overview. *Renewable and Sustainable Energy Reviews , 15*, 471-481.

Kramreiter, R., Url, M., Kotik, J., & Hofbauer, H. (2008). Experimental investigation of a 125 kW twin-fire fixed bed gasification pilot plant and comparison to the results of a 2 MW combined heat and power plant (CHP). *Fuel Processing Technology , 89*, 90-102.

Kumar, A., Jones, D. D., & Hanna, M. A. (2009). Thermochemical Biomass Gasification: A review of the current status of the technology. *Energies , 2*, 556-581.

Larsson, S., Fantazzini, D., Davidsson, S., Kullander, S., & Hook, M. (2014). Reviewing electricity production cost assessments. *Renewable & Sustainable Energy Reviews , 30*, 170-183.

Monteiro, E., Moreira, N. A., & Ferreira, S. (2009). Planning of micro-combined heat and power systems in the Portuguese scenario. *Applied Energy , 86*, 290-298.

Nel, W., & Cooper, C. (2009). Implications of fossil fuel constraints on economic growth and global warming. *Energy Policy , 37* (1), 166-180.

Pereira, E. G., Silva, J. N., Oliveira, J. L., & Machado, C. S. (2012). Sustainable energy: A review of gasification technologies. *Renewable and Sustainable Energy Reviews , 16*, 4753-4762.

Puig-Arnavat, M., Bruno, J., & Coronas, A. (2010). Review and analysis of biomass gasification models. *Renewable and Sustainable Energy Reviews , 14*, 2841-2851.

Purohit, P. (2009). Economic potential of biomass gasification projects under clean development mechanism in India. *Journal of Cleaner Production , 17*, 181-193.

Roos, C. J. (2010). *Clean Heat and Power Using Biomass Gasification for Industrial and Agricultural Projects.* Clean Energy Application Center, U.S. Department of Energy. WA: Northwest.

Ruiz, J. A., Juarez, M. C., Morales, M. P., Munoz, P., & Mendivil, M. A. (2013). Biomass gasification for electricity generation: Review of current technology barriers. *Renewable and Sustainable Energy Reviews , 18*, 174-183.

Salomon, M., Savola, T., Martin, A., Fogelholm, C. J., & Fransson, T. (2011). Small-scale biomass CHP plants in Sweden and Finland. *Renewable & Sustainable Energy Reviews , 15*, 4451-4465.

Shafie, S. M., Mahlia, T. M., Masjuki, H. H., & Yazid, A. A. (2012). A review on electricity generation based on biomass residue in Malaysia. *Renewable and Sustainable Energy Reviews , 16*, 5879-5889.