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A K M S HOSSAIN

A Model for Sustainable Biomass Electricity Generation in Bangladesh

SCHOOL OF ENGINEERING

PhD THESIS

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Academic Year 2004-2005

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September 2005

This thesis is submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy

ABSTRACT

Bangladesh, where only 20% of the total population are connected to grid electricity, has a promising scope to utilise biomass for decentralised electricity generation. In this study, sustainable biomass electricity generation model was developed for the country, by combining techno-econometric and optimisation modelling techniques. The developed model addresses the biomass generation and availability, feasible technologies, cost and efficiency correlations, economic plant size, plant economics and sensitivity, and environmental and social impacts.

In 2003, the national total annual available biomass energy potential in Bangladesh varies from 183.848 to 223.776 TWh. The feasible technologies are: gasification based ICE-generator, anaerobic digestion based ICE-generator and direct combustion based steam turbine or Stirling engine-generator. Correlations of capital investment costs and overall conversion efficiencies with the plant electricity generating capacity have been developed. Direct combustion technology shows the highest electricity generation potential of 20.21 TWh/year; followed by gasification, of 14.30 TWh/year. Economic radius of biomass collection and size of the plants has been determined for maximum profitability. The biomass electricity plants economics have been estimated and compared with the diesel and dual-fuelled plants. Analysis shows that, anaerobic digestion and gasification-based electricity generation plants are economically feasible. Biomass electricity plant is highly sensitive to changes in biomass price, selling price of electricity, investment cost, plant lifetime, conversion efficiency and operating hours. The employment of the biomass electricity instead of diesel generator saves significant amount of the greenhouse gas emissions. It creates more employment than conventional and presents other socio-economic benefits as well.

Due to the combination of electricity generation potential, promising economics and low greenhouse gas emissions; gasification-based biomass electricity plant is recommended for the country. Biomass availability and plant economics vary between districts to districts. Computer programmes have been developed for district wise biomass electricity plant analysis.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude and heartiest thanks to my supervisor Dr. Ossama Badr, for his advice, generous help and support, and encouragement throughout the course of my study.

I am very grateful to the Department of Process and Systems Engineering and School of Engineering for waiving my tuition fees during the last two years of my study at Cranfield University. Special thanks and gratitude are due to my supervisor Dr. Ossama Badr, Professor Michel Sanderson (Head of the Department), and Professor Minno Patel (Head of School); all of whom helped me to continue my study at Cranfield.

I would also like to express my love and gratitude to my wife Surya Akter and to my little daughters Juwairiyah and Maimoonah for their support and patience during the time I spent working in this research study. I owe to my wife Surya, who provided a valuable support during my study at Cranfield.

Special thanks are due to Linda, Janet and Krystle of the Department of Process and Systems Engineering for their support during my study at Cranfield University. My thanks are also due to the members of staff of the Cranfield University Library for providing the requested information related to my study.

Also, I am grateful to BAEC, Bangladesh; for the support and co-operation during my research.

Last, but by no means least, I would like to thank my parents, parents-in-law and friends for encouraging me in keeping studying.

CONTENTS

ABBREVIATIONS

AD	Anaerobic Digestion
BAEC	Bangladesh Atomic Energy Commission
BARD	Bangladesh Academy for Rural Development
BAU	Bangladesh Agricultural University
BCAS	Bangladesh Centre for Advanced Studies
BCSIR	Bangladesh Council for Scientific and Industrial Research
BDT	Bangladeshi Taka (name of currency)
BFB	Bubbling Fluidised Bed
BG	Biogas
BIT	Bangladesh Institute of Technology
BPDB	Bangladesh Power Development Board
BRAC	Bangladesh Rural Advancement Committee
BUET	Bangladesh University of Engineering and Technology
BWDB	Bangladesh Water Development Board
CES	Centre for Energy Studies
CFB	Circulating Fluidised Bed
CHP	Combined Heat and Power
C/N	Carbon-to-nitrogen
CoE	Cost of Electricity
DANIDA	Danish International Development Agency
DC	Direct Combustion
DESA	Dhaka Electric Supply Authority
DOE	Department of Environment, Bangladesh
DSS	Decision Support System
DU	Dhaka University
FAO	Food and Agricultural Organisation
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographical Information System
GOB	Government of Bangladesh
GS	Grameen Shakti
GWP	Global Warming Potential
HHV	Higher Heating Value
HRSG	Heat Recovery Steam Generator

IC	Internal Combustion
ICE	Internal Combustion Engine
IFRD	Institute of Fuel Research and Development
IPP	Independent Power Producer
ktonne	Kilo (1000) tonne
LEAP	Long-range Energy Alternative Planning
LGED	Local Government Engineering Department
LHV	Lower Heating Value
MCFC	Molten Carbonate Fuel Cell
MC_w	Moisture Content (wet basis)
MSW	Municipal Solid Waste
Mtoe	Million tonnes of oil equivalent
Mtonne	Million tonne
NGO	Non Government Organisation
O & M	Operation and Maintenance
PAFC	Phosphoric Acid Fuel Cell
PBP	Pay Back Period
PG	Producer Gas
PV	Photovoltaic
RDF	Refuse Derived Fuel
REB	Rural Electrification Board
RERC	Renewable Energy Research Centre
SHS	Solar Home Systems
SIS	Social Impact Studies
SOFC	Solid Oxide Fuel Cell
SRE	Sustainable Rural Energy
TCoE	Total Cost of Electricity
TS	Total Solid
UNDP	United Nations Development Program
VS	Volatile Solid

NOTATIONS

AC	Annualised capital cost	(US$/yr)
AC_d	Ash content (dry basis)	(%)
A_d	Area of the district	(km^2)
A_e	Economic area of biomass collection	(km^2)
C_{bs}	Price of biomass	(US$/tonne)
CF	Cash Flow	(US$)
CI	Cash Inflow	(US$)
CO	Cash Out flow/Expenditure	(US$)
C_r	Cost of repair and maintenance	(US$/yr)
CRF	Capital recovery factor	-
C_{ss}	Cost of biomass storage	(US$/tonne)
C_{ts}	Cost of transportation	(US$/tonne/km)
C_{ws}	Mean annual per capita cost of operator	(US$/capita/yr)
df	De-rating factor	-
E	Annual amount of generated electricity	(kWh/yr)
f_a	Present worth factor	-
FC	Cost of fuel	(US$/yr)
H_b	Lower heating value of biomass	(kWh/tonne)
H_{bg}	Lower heating value of the biogas	(kWh/m^3)
H_d	Lower heating value of diesel	(kWh/tonne)
H_{sg}	Lower heating value of the producer gas	(kWh/m^3)
i	Real interest rate	(%)
I	Total capital investment	(US$)
$I_s(SCI)$	Specific capital investment	(US$/kW)
k_f	Co-efficient of others fixed cost (as % of the total capital investment)	(%)
k_r	Co-efficient of repair and maintenance cost (as % of the total capital investment)	(%)
m_b	Mass flow rate of consumption of biomass fuel	(tonne/yr)

M_b	Quantity of biomass needed to generate 1 kWh electricity in a dual-fuelled engine generator	(kg)
m_{bg}	Volume flow rate of the biogas produced	(m^3/yr)
M_d	Quantity of diesel needed to generate 1 kWh electricity in a dual-fuelled engine generator	(kg)
m_{sg}	Volume flow rate of the producer gas produced	(m^3/yr)
n	Useful life of the plant	(yr)
NPV	Net Present Value	(US$)
N_u	Number of operators	-
OC	Cost of operation	(US$/yr)
OFC	Others fixed costs	(US$/yr)
P	Electricity generating capacity of the plant	(kW)
P_e	Economic size of the plant	(kW)
PI	Profitability Index	-
Q_b	Thermal energy content of the biomass available in the circular area ($= \sigma \pi r^2 H_b$)	(kWh)
Q_{bg}	Thermal energy content of the biogas generated	(kWh)
Q_d	Thermal energy input of diesel to a dual-fuelled engine-generator to generate 1 kWh electricity	(kWh)
Q_g	Thermal energy input of producer gas to a dual-fuelled engine-generator to generate 1 kWh electricity	(kWh)
Q_{sg}	Thermal energy content of the producer gas generated	(kWh)
Q_t	Total thermal energy input of diesel and producer gas (or biogas) to a dual-fuelled engine-generator to generate 1 kWh electricity	(kWh)
r	Radius of biomass collection	(km)
r_e	Economic radius of biomass collection	(km)
rf	Diesel replacement factor	-
S_{ue}	Selling price of generated electricity	(US$/kWh)
t	Annual operating time of the plant	(hr/yr)
W_s	Annual amount of biomass needed for storage	(tonne/yr)
W_{UGE}	Useful work output (equivalent energy) of the gas engine	(kWh)
W_{UGT}	Useful work output (equivalent energy) of the gas turbine	(kWh)
W_{USE}	Useful work output (equivalent energy) of the Stirling engine	(kWh)

W_{UST}	Useful work output (equivalent energy) of the steam turbine	(kWh)
η_c	Efficiency of conversion of biomass fuel into useful mechanical energy	(%)
η_D	Thermal efficiency of the digester	(%)
η_d	Thermal efficiency of diesel engine	(%)
η_{dfe}	Thermal efficiency of dual-fuelled engine	(%)
η_e	Efficiency of electricity generator	(%)
η_G	Thermal efficiency of the gasifier	(%)
η_{GE}	Thermal efficiency of the gas engine	(%)
η_{GT}	Thermal efficiency of the gas turbine	(%)
η_0	Overall conversion efficiency	(%)
η_{SE}	Thermal efficiency of the Stirling engine	(%)
η_{ST}	Thermal efficiency of the steam turbine	(%)
σ	Density of the available biomass	(tonne/km^2/yr)
λ	Excess air factor	-

CHAPTER 1
GENERAL INTRODUCTION AND THESIS OVERVIEW

1.1 Background

World energy demand is likely to grow faster than the increase in population. In 2004, the total world-wide consumption of commercial primary energy sources was estimated to be 10224 mtoe (BP Amoco, 2005). Of the total, fossil fuels amount to ~88%, whereas the share of nuclear and hydro-electricity are small (see Table 1.1). There are two factors affecting the availability of fossil fuels – one is the limited nature of their reserves and the other is the security of supply. Eight countries have 81% of all the global crude oil reserves, six countries have 70% of all natural gas reserves and eight countries have 89% of all coal reserves. More than half of Asia, Africa and Latin America import over half of all their commercial primary energy needs (Sayigh, 1999).

New and renewable energies will therefore become one of the world's main energy sources. At present, renewable energy contributes only 11% to world primary energy, it is expected that 60% of all world energy will come from renewable energy sources by the year 2070 (WREN, 2002).

Electricity is a necessary commodity for the economic and social development of nations. There are globally more than 2 billion people without access to any form of electricity and many more without the convenience of a grid connection (Harvey, 1995). It is quite possible that in 40 years time the former figure could increase to 5 billion.

Bangladesh, a least developing country in South Asia, has been experiencing a severe electricity crisis. Only 20% of the total population is supplied with grid electricity (EIA, 2004). In rural areas of the country, where ~80% of the total population resides, the fraction drops to a mere 10%. Of the total installed electricity-generation capacity, 95% of the power plants use fossil fuels, of which share of natural gas is around 85%

Source	Consumption	
	mtoe	% of total
Fossil fuels :		
Oil	3767.1	36.84
Coal	2778.2	27.17
Natural gas	2420.4	23.67
Nuclear energy[a]	624.3	6.11
Hydro-electricity[a]	634.4	6.21
Total	10224.4	100.00

[a] converted on the basis of thermal equivalence assuming 38% conversion efficiency in a modern thermal power station to generate the same amount of electricity.

Table 1.1 World-wide consumption of commercial primary energy in 2004 (BP Amoco, 2005)

(BPDB, 2005). At an annual 10% growth rate of consumption, the national reserve of natural gas may not last more than 15-20 years (Bhuiyan et al. 2000). The World Bank has estimated that Bangladesh loses around US$1 billion per year in economic output due to power shortages and unreliable power supply (EIA, 2004). The Government of Bangladesh has a vision to electrify the whole of the country by the year 2020 (MOF, 2005).

Electrification of villages in remote areas usually requires large investment and leads to power losses associated in transmission and distribution networks. One of the great promises offered by the renewable energy technologies is their potential to provide electricity in areas not served by national power grids. The draft Renewable Energy Policy of Bangladesh, published in 2002, stated that renewable energy will take a vital role for off-grid electrification in the country. The main renewable energy resources in Bangladesh are biomass, solar, wind and hydro-power. Hydro-power potential of Bangladesh is low due to the relative flatness of the country. Most potential sites for wind power utilisation are situated in the coastal regions. Wind power generation and its application in Bangladesh have certain limitations due to lack of reliable wind speed data and seasonal variation of wind speed. The country has good prospects of utilising solar PV systems for electricity generation, but the high capital investment cost of solar PV is a big barrier for adopting such systems. Biomass is the major energy source in Bangladesh and biomass utilisation systems represent a proven option for small to medium-scale decentralised electricity generation.

Biomass refers to all forms of living matter (i.e. plants and animals), as well as the corresponding derived material (e.g. plant residues, human wastes and animal dung) on earth. It represents only a very small fraction of the total mass of the planet, but in human terms, it is an enormous store of the energy supplied principally by the Sun and is being replenished continually. Biomass is a versatile source of energy; it can be used as a solid fuel or converted into liquid or gaseous fuels. The utilisation of biomass, as a substitute for fossil fuels, plays an important role in CO_2 mitigation. If grown in a sustainable manner, the production and utilisation of biomass create no net accumulation of CO_2 in the atmosphere (Yokoyama et al. 2000). During the next century, biomass-energy is expected to offer cost-effective and sustainable opportunities with the potential to meet 50% of world energy demands and the requirement of reducing carbon emissions from fossil fuels (IEA Bioenergy, 2005). Biomass energy systems can play an important role of a country's or region's development, i.e. education, employment and economic growth through business expansion (i.e. earnings), direct and indirect effects on GDP, support of traditional industries, rural diversification, and community empowerment.

Decentralized small-scale electricity production is currently a common practice in many countries of the world, especially where a well-established electricity grid is absent. The employment of biomass fuels is a proven option for decentralized small to medium-scale electricity generation. Bangladesh is ideally suited for the development of small-scale biomass energy systems (EIA, 2003). No study has been carried out to assess the technological and economical feasibility of biomass electricity generation in Bangladesh. This study proposes sustainable biomass electricity generation model for decentralized electricity generation in Bangladesh, by exploring the net biomass availability, feasible technologies, economic plant size, cost of electricity generation, sensitivity parameters and environmental and socio-economic impact analysis.

1.2 Objectives of the Current Study

The objectives of this research work are:

- Study the primary energy and electricity situation in Bangladesh
- Study the renewable energy sources, their potential and current utilisation in Bangladesh
- Estimate the annual rate of biomass generation and recovery and amount available for electricity generation in Bangladesh
- Review the available biomass-to-electricity generation technology and modelling techniques
- Selection of the feasible conversion technologies for Bangladesh
- Developing correlations for efficiency and capital investment costs of these feasible technologies with electricity generation capacity
- Estimation of the electricity generation potential for each type of feasible technologies in the country
- Estimation of the economic size of the biomass electricity plant and optimum value of other parameters for each type of feasible technology
- Assessing the biomass electricity plant economics and comparing it with those for diesel and dual-fuelled (biogas or producer-gas and diesel) based electricity generating plants
- Performing the sensitivity analysis, to identify the parameters having the highest influence on the economics of the biomass electricity plant
- Carrying out environmental and socio-economic impact analyses of the biomass electricity plant

1.3 Thesis Structures

Geographical information together with econometric and optimization techniques has been used in this research study. Bangladesh is divided into six divisions/regions, in these divisions there are 64 districts. Biomass availability of each district has been estimated for investigating the possibility of installing decentralised biomass electricity generation plants. Capital investment costs and conversion efficiencies of the feasible technologies are important for economical analysis. No well established correlations were found in the literature. Costs and efficiency correlations with the plant electricity generating capacity have been developed for different types of prime mover using various biomass fuels. Economic size of the plant has been estimated for maximum profitability. Economic size, area of biomass collection, number of biomass electricity plants have been estimated for each district for all types of feasible technologies. Later, economical analysis, sensitivity, environmental and socio-economic studies have been performed. Matlab software has been employed for this study.

The thesis is divided into ten chapters and six appendices. Chapter 1 is the general introduction of the thesis which describes the background, objectives and thesis structure.

Chapter 2 reviews the energy situation in Bangladesh. Issues related to primary energy consumption and reserves, fuels and technology used for electricity generation, electricity consumption, and renewable energy utilisation are presented. Chapter 3 reviews the technologies available for converting biomass into electricity. A brief description of each conversion technology, which includes principle of conversion, technology, scale of biomass electricity generation plant, advantages and disadvantages are presented.

Chapter 4 reviews the biomass energy systems modelling techniques. Existing modeling practices both in Bangladesh and in other countries have been reviewed and grouped. At the end of this chapter, techniques, which would be used to develop sustainable biomass electricity modeling for Bangladesh, have been discussed.

Chapter 5 presents the methods adopted for estimating the annual rate of biomass generation and recovery in Bangladesh. The annual amount of biomass available for electricity generation has been estimated for the whole country and for each individual district. Seasonal availability and storage options of the biomass resources have been discussed. Biomass savings through efficiency improvements of the traditional uses of biomass have also been presented.

Chapter 6 deals with discovering the feasible biomass energy technologies for Bangladesh. An in-depth analysis of the feasible technologies has been presented. Suitability and groupings of the available biomass resources has been performed for each type of the feasible technologies. Efficiency and costs correlations have been developed after examining the biomass electricity plants, especially in the developing countries. Finally, electricity generation potential for the whole country has been presented - for each type of the feasible technologies using different types of biomass.

In Chapter 7, a generalised profitability equation has been derived for all types of feasible technologies. Optimisation technique (i.e. maximising the profitability) has been applied to estimate the economic size of the biomass electricity plant.

Chapter 8 presents the economical analysis of the biomass electricity plants. Biomass electricity plant economics have been compared with those for the dual-fuelled systems and diesel generation systems. Sensitivity analyses have also been performed.

Chapter 9 presents the environmental and socio-economic impact study of the proposed biomass electricity plants. Impacts of the solid, gaseous and liquid effluents, of a biomass electricity plant, on the environment, have been investigated. The greenhouse gas emission savings potential has been estimated. In the second part of this chapter, various socio-economic benefits of the biomass electricity plants have been presented with examples of the installed plants in neighboring country.

Finally, Chapter 10 presents the conclusions of this research work, and recommendations for future work.

Of the appendices, Appendix A explains the glossary of terms used in the thesis. Appendix B describes outlines of the developed computer program and the procedures to be followed to use the attached CD-ROM, for district wise biomass electricity analysis in Bangladesh. Appendix C presents district wise biomass generation and Appendix D presents the capital investment cost and conversion efficiency of the installed biomass electricity plants in different parts of the world. Appendix E presents district wise results of biomass electricity analysis in Khulna division. Appendix F shows biomass energy and electricity potential by division.

CHAPTER 2
ENERGY OVERVIEW OF BANGLADESH

2.1 Bangladesh: An Introduction

The People's Republic of Bangladesh, a south Asian country, is located between 23°34'N and 26°38'N latitudes and 88°01'E and 92°41'E longitudes (BBS, 2002). Bangladesh is bounded by India in the north, east and west and by the Bay of Bengal in the south, and shares a small border in the east, with Myanmar (Burma) - see Figure 2.1. The capital city is Dhaka. The country is divided into 6 divisions (regions): Dhaka, Chittagong, Rajshahi, Barisal, Sylhet and Khulna. In these regions, there are 64 districts (see Figure 2.1).

The total area of the country is 1.44 x 10^{11} m^2 (FAOSTAT, 2004). In 2003/2004, the population of Bangladesh reached 138.1 million (i.e. 959 people/km^2), making it the most densely-populated country in the world. 80% of the total population resided in rural areas. The annual population growth rate in 2003/2004 was 1.7% (BBS, 2002; World Bank, 2005).

The climate in the country follows a four-season cycle: winter (December-February), summer (March-May), monsoon (June-September) and autumn (October-November). In winter, the average maximum and minimum temperatures are 26.5°C and 13.5°C respectively, whereas the corresponding respective values in summer are 33.3°C and 22.2°C (SDNBD, 2005a). Most of the rainfall occurs during the monsoon season. Annual rainfall ranges from 160 cm to 200 cm in the west, 200 cm to 400 cm in the south-east and 250 cm to 400 cm in the north-east (SDNBD, 2005a). In 2002/2003, adult (aged 15 and above) male and female literacy rate were 50.3% and 31.4% respectively (World Bank, 2005).

Bangladesh's economy grew at an average annual rate of 4% in the 1980s and 5% in the 1990s (EIU, 1999). The higher rate of growth in the 1990s has often been attributed to the rapid liberalization of the economy in the early years of the decade. Sectoral growth also improved in the 1990s with an annual average rate of 7% compared with 2% in the 1980s. Export growth followed a similar trend; reaching an annual average rate of 16% in the 1990s, compared with 7% in the 1980s (EIU, 1999). The sectors of the country's economy are agriculture and forestry, fishing, mining and quarrying, manufacturing, construction, electricity and gas, transport and communication, wholesale and retail trade, financial services, and other services (e.g. tourism, real state business).

During the last five years, Bangladesh averaged over 5% growth in the gross domestic product (GDP). In the financial year 2003/04, GDP grew at an average rate 5.5% - an increase of 20% than the previous year (Global Insight, 2005). The agriculture and forestry sector (including crop, fisheries and livestock), the single largest contributor to GDP growth - accounted for 31.5% of GDP in 1998/99, down from 34.5% in 1991/92. The crop sub-sector contributed 22.8% of GDP in 1998/99 compared with 27.9% in 1992/93 (EIU, 1999).

Map No. 3711 Rev. 2 UNITED NATIONS
January 2004

Department of Peacekeeping Operations
Cartographic Section

Figure 2.1 Location, regions and districts of the People's Republic of Bangladesh (UN, 2004)

The national currency of the country is Taka, its exchange rate is, 1US$ = Taka 63.945 (as on 06/07/2005). Per capita gross national income (GNI) is in the increasing trend: in 2003/2004 the per capita GNI was US$400.00; whereas, it was US$ 380.00 and US$ 370.00 in 2002/2003 and in 2001/2002 respectively (World Bank, 2005). Inflation rates during financial years 2002/2003 and 2003/2004 were 5.67% and 6.10% respectively (Global Insight, 2005). Total imports amounted to US$ 9,720 million and US$ 10,190 million, in 2002/2003 and in 2003/2004 respectively. Export earnings rose by 1.63%

during 2002/2003 to US$ 6,850 million, and it was US$ 7,350 million in 2003/2004 (Global Insight, 2005). Agriculture and the garments making industry are the two dominant sectors of export earnings.

2.2 Commercial Primary Energy Resources and Use

Indigenous commercial primary energy resources of Bangladesh consist of the known reserves of natural gas and coal, and a limited hydro-electric capacity. The entire reserves of exploitable indigenous fossil-fuels, with the exception of the coal reserve, are located in the eastern part of the country. This results in a gap of commercial-energy supply between the east and the west. Natural gas is the main commercial primary energy source of Bangladesh.

Total commercial primary energy consumption in Bangladesh increased at an average rate of 0.74 million tonnes of oil equivalent (mtoe) per year between 1992 and 2004 (see Figure 2.2). The trend is mainly due the increased consumption of natural gas and imported oil. The contribution of hydropower to total commercial primary energy consumption is almost constant. At the end of year 2004 and 2003, the total national commercial primary energy consumption was 16.8 and 15.8 mtoe respectively (BP Amoco, 2005). In 2004, the shares of natural gas, oil, coal and hydro-electricity were 70.8, 25, 2.4 and 1.8%, respectively (BP Amoco, 2005). Per capita annual energy consumption of commercial primary energy (i.e. fossil fuels and hydro electricity) in Bangladesh, in 2003, was 0.114 tonnes of oil equivalent (toe) (BP Amoco, 2005). This is one of the lowest in the world, compared with a world average of 1.556 toe/capita/year (BP Amoco, 2005; World Bank, 2004). In 2002, the average consumptions for low income countries and south Asian countries were 0.493 and 0.468 toe/capita, respectively (World Bank, 2004).

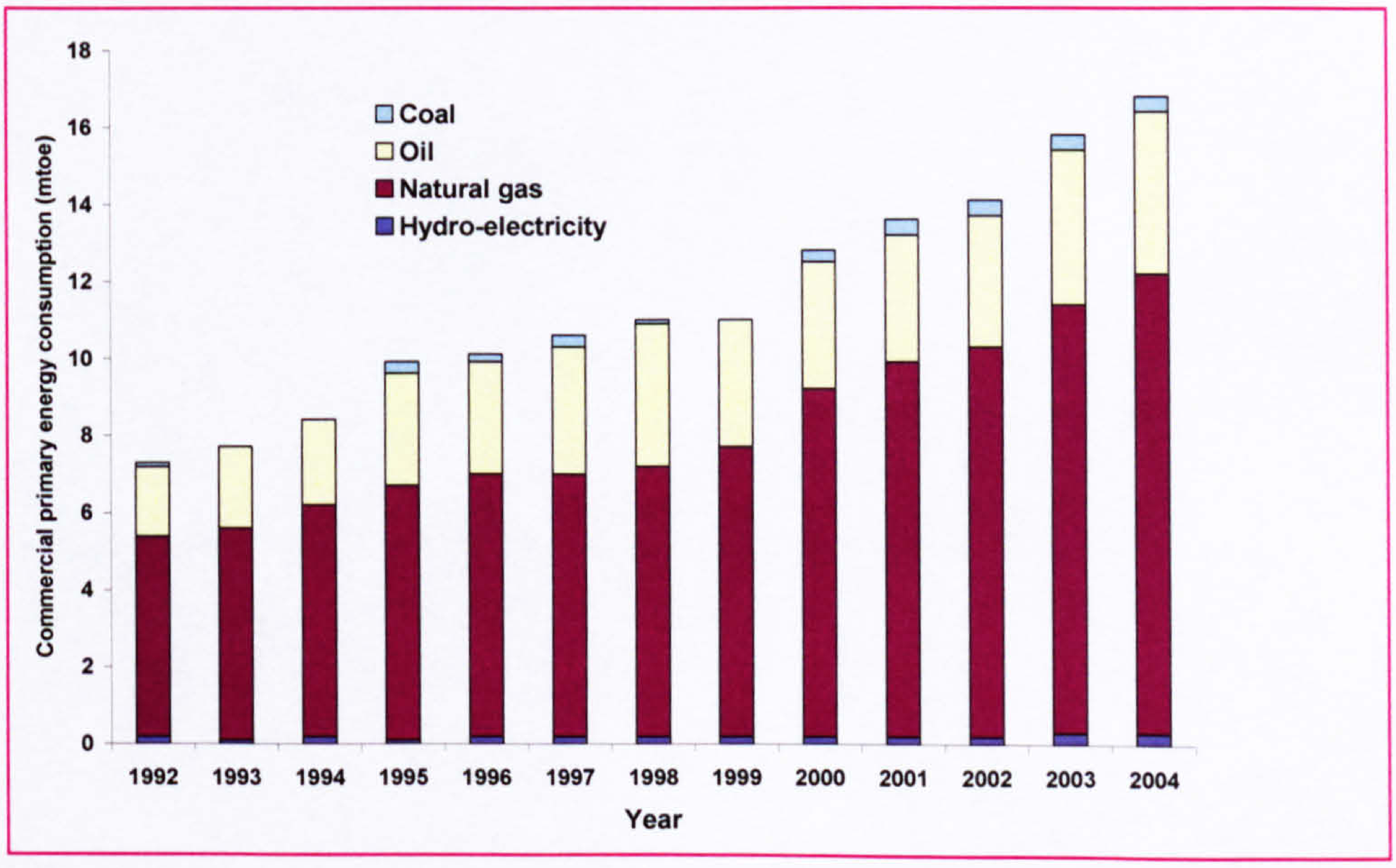


Figure 2.2 Commercial primary energy consumption trends in Bangladesh (BP Amoco, 2005)

2.2.1 Natural Gas

Natural gas plays an important role in the growth of the national economy. 84.5% of power generation (BPDB, 2005) and the whole of the urea fertilizer manufacturing are based on natural gas. Up to June 2004, 22 natural gas fields have been discovered in Bangladesh (MOF, 2005). The total estimated amount of gas within these fields is 804.71 billion m^3, of which 580.78 billion m^3 is believed to be recoverable (MOF, 2005). Up to June 2004, the cumulative total amount of gas produced was 157.03 billion m^3 (see Table 2.1). So, as of June 2004, the net recoverable gas reserve is 423 billion m^3.

Government of Bangladesh (GOB) allowed the participation of international oil companies in the exploration and development of the hydrocarbon sector. The total area of Bangladesh has been divided into 23 zones for rapid and easy exploration. At present, many international oil companies (e.g. Shell, Tullow, Cairn and Texaco) are exploring in different zones under production-sharing contracts (MOF, 2005).

Power plants, fertiliser factories, other industries (e.g. brick factories, tea processing plants, steel mills and textile factories), commercial organisations (e.g. offices and business centre) and the domestic sector are the end user of natural gas in the country. Sector wise consumption of natural gas is shown in Figure 2.3.

Name of the gas field	Natural gas reserve and production (billion m^3)			
	Total estimated reserve	Recoverable reserve	Cumulative production	Net recoverable
Bakhrabad	42.447	29.704	17.858	11.846
Habigonj	145.520	109.076	32.340	76.736
Jalalabad	33.839	23.701	5.401	18.300
Kailashtila	77.022	53.915	9.274	44.641
Meghna	4.842	3.370	0.933	2.437
Narshingdi	8.693	6.088	1.427	4.661
Rashidpur	56.690	39.672	9.189	30.483
Sylhet	19.369	13.564	4.915	8.649
Sangu	29.195	24.013	7.748	16.265
Salda Nadi	4.701	3.285	0.987	2.298
Titas	207.421	145.209	63.694	81.515
Beani Bazar	6.881	4.814	0.777	4.037
Fenchuganj	11.440	8.014	0.024	7.990
Begumgonj	1.331	0.934	-	0.934
Kutubdia	1.841	1.303	-	1.303
Semutang	6.428	4.248	-	4.248
Shahbazpur	18.831	13.167	-	13.167
Bibiana	89.056	67.989	-	67.989
Moulovibazar	12.714	10.194	-	10.194
Chatak	19.171	13.422	0.750	12.672
Kamta	2.039	1.416	0.597	3.084
Feni	5.239	3.681	1.119	0.297
Total	**804.708**	**580.779**	**157.033**	**423.745**

Table 2.1 Natural gas fields of Bangladesh (MOF, 2005)

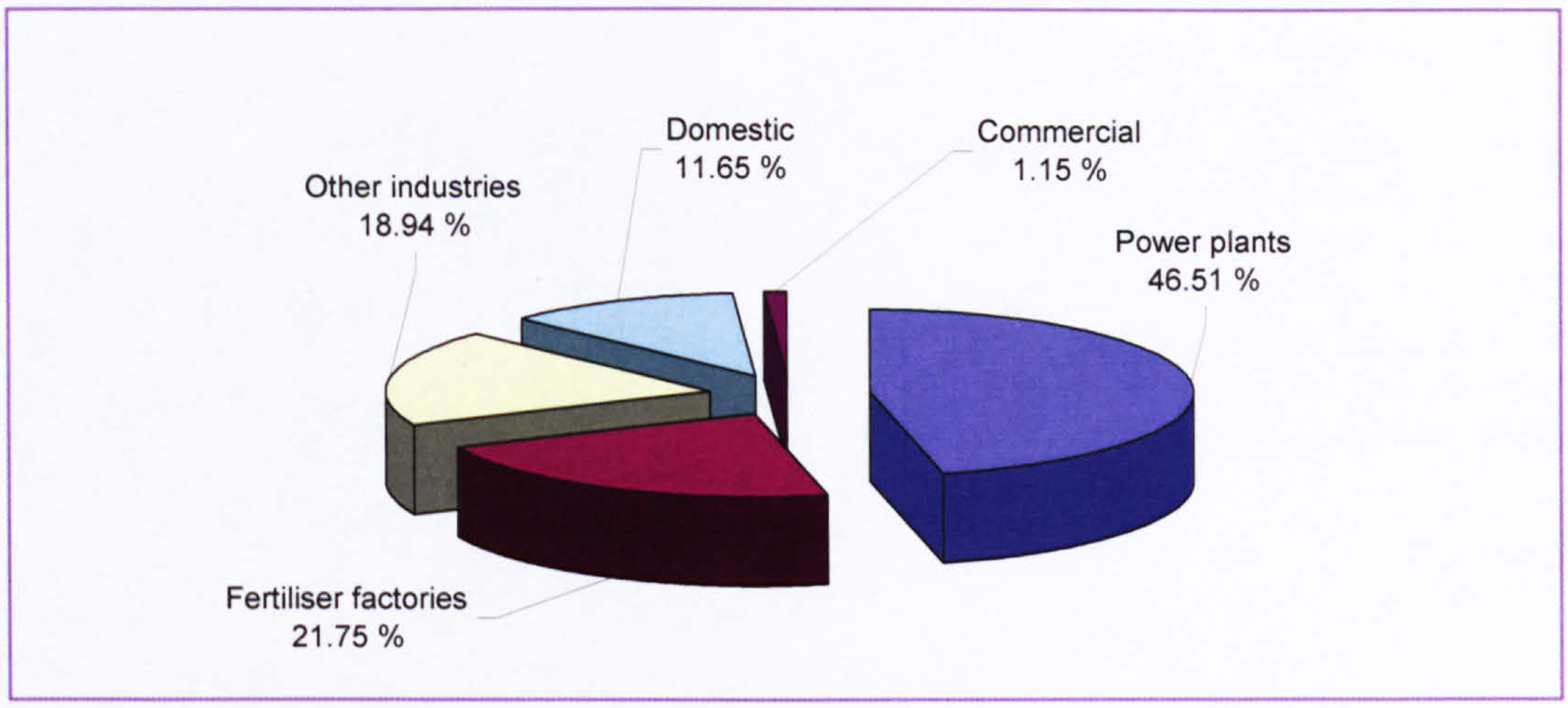


Figure 2.3 Consumption of natural gas in 2003/04 (MOF, 2005)

2.2.2 Oil

Bangladesh's only oil deposits, discovered in December 1986, located at Haripur, in the district of Sylhet, has an estimated amount of total reserve of 1.4 million tonnes of which 0.84 million tones is believed to be recoverable. Up to July 1994, the cumulative total amount of crude oil produced was 0.0784 million tonnes of crude oil (REIN, 2003a). Since then, oil production ceased because of the reduction of pressure in the field and influx of water in the oil zone. In Bangladesh, oil is used mainly as a transport fuel, for some electricity generation and for industrial heating.

2.2.3 Coal

Substantial amount of coal reserves, in 7 fields, have been discovered in the north-western part of the country - see Table 2.2. The major coal deposits are at: Jamalgonj (in the Jaipurhat district), Baropukuria (in the Dinajpur district) and in Khalashpir (in the Rangpur district). The total amount coal reserve is estimated at 1,756 Mtonnes (REIN, 2005a).

Mining work has started only at Baropukuria. Baropukuria coal field was discovered in 1985 by Bangladesh Geological Survey Department. Coal extraction from Baropukuria deposit, at an estimated rate of 1 Mtonnes/year, is expected to commence in 2004/2005. 70% of extracted coal will be used in a 250 MW coal-fired power plant (MOF, 2005; REIN, 2005a).

Coal field	Depth of coal layer (m)	Type of coal	Area (km^2)	Reserve (Mtonnes)
Jamalgonj, Jaipurhat	640 -1158	Bituminous	11.66	1053
Baropukuria, Dinajpur	118 - 506	Bituminous	5.25	300
Khalashpir, Rangpur	257 - 451	Bituminous	5.75	400
Kuchma, Bogra	2381 – 2876	Bituminous	-	-
Dighirpara, Dinajpur	250	Bituminous	15.00	-
Phulbari, Dinajpur	> 150	Bituminous	-	-
Takerhat, Sunamgonj	45 - 97	Lignite	-	3

Table 2.2 Coal fields of Bangladesh (REIN, 2005a)

In 1997, BHP Minerals (a US-Australian Company) - discovered a coal reserve at Phulbari in the Dinajpur district. Later, BHP Minerals transferred the rights to develop the coal field to Asia Energy Corporation (AEC) Bangladesh Ltd., a subsidiary of AEC, Australia. A preliminary study, conducted by AEC, concluded that coal extraction from Phulbari coal-field is technically and economically feasible. In 1998, an agreement was signed between the GOB and AEC to develop the field and extract the coal. AEC proposed to set up 2100 MW coal-fired power-generation facility. According to AEC plan, 2.9 Mtonnes of coal will be extracted per year to fuel a 700 MW power plant. After 7 years, the coal production will be increased to 9 Mtonnes/year and power plant capacity will be enhanced to 2100 MW (REIN, 2005a).

2.2.4 Peat

In Bangladesh, deposits of peat occur at shallow depths in different low lying areas of the Faridpur, Madaripur, Khulna, Sylhet, Maulavibazar, Mymensing, Rangpur, Barishal, comilla and Dhaka districts. The total peat reserves have been estimated at 170 Mtonnes (REIN, 2003b).

Peat remains under water for about 6 months of the year, so drying the extracted peat is time consuming and involves cost. In 1985/86, a feasibility study for the extraction and utilisation of the peat resources of Bangladesh was carried out by M/S. SNC W. P., UK under the Canadian International Development Agency (CIDA) technical assistance programme. The study recommended the setting up of a pilot plant for the extraction and briquetting of peat and the installation of a 10 MW peat-fired power plant. Accordingly, peat utilisation and demonstration project was implemented by Petrobangla in the Madaripur district. During March-June 1993, about 300 tonnes of peat was extracted. Further 2000 tonnes of peat was extracted in the following session (REIN, 2003b). Efforts were made for marketing peat briquettes as domestic and brick-making fuel. However, the results were not encouraging and extraction was assessed as economically non-viable. Nevertheless, with the rise of the prices of fossil fuels, peat may prove viable in the future. In some rural areas, locally extracted peat is used for domestic cooking and in small industries.

2.2.5 Hydro-power

Due to relative flatness of the country, Bangladesh has got a limited hydro-power resource. The only 230 MW hydroelectric power plant, Kaptai Dam, located on the river Karnaphuli, at kaptai, in the Chittagong district, was commissioned on 30 March 1962 (REIN, 2003c). It has a catchment area of 11×10^3 km^2 and a capacity of 6.5×10^9 m^3. The plant is operated by Bangladesh Power Development Board (BPDB), and represents approximately 5% of the total installed capacity in 2003 (BPDB, 2005). In addition to power generation, the dam was supposed to provide additional benefits in terms of flood control, irrigation and drainage, navigation and enhanced forest resource harvesting. Most of these objectives have been served in various degrees except irrigation and drainage. Later, commercial fish farming and recreation activities have been introduced in the project.

2.3 Electricity Generation and Consumption

In 1947 (i.e. the time of partition of the Indian sub-continent), power generation and distribution in Bangladesh (i.e. formerly East Pakistan) were undertaken by a number of private companies. The power supply to the then 17 provincial districts of East Pakistan was only within townships (with no transmission system). The generation voltage was 400 volts. The total generation capacity of the power utility companies put together was only 7 MW. In 1948, the Electricity Directorate was established in order to plan and improve the power supply situation. In 1959, the Water and Power Development Authority (WAPDA) was created, and in 1960 Electricity Directorate was merged with WAPDA to give more autonomy for the development of the basic infrastructure. During the 1960s, relatively higher capacity oil and gas fired plants were built in the Dhaka, Chittagong and Khulna districts; and the Kaptai Dam was constructed. The installation of Dhaka-Chittagong 132 kV transmission line was also completed during that period (REIN, 2003d; BPDB, 2005).

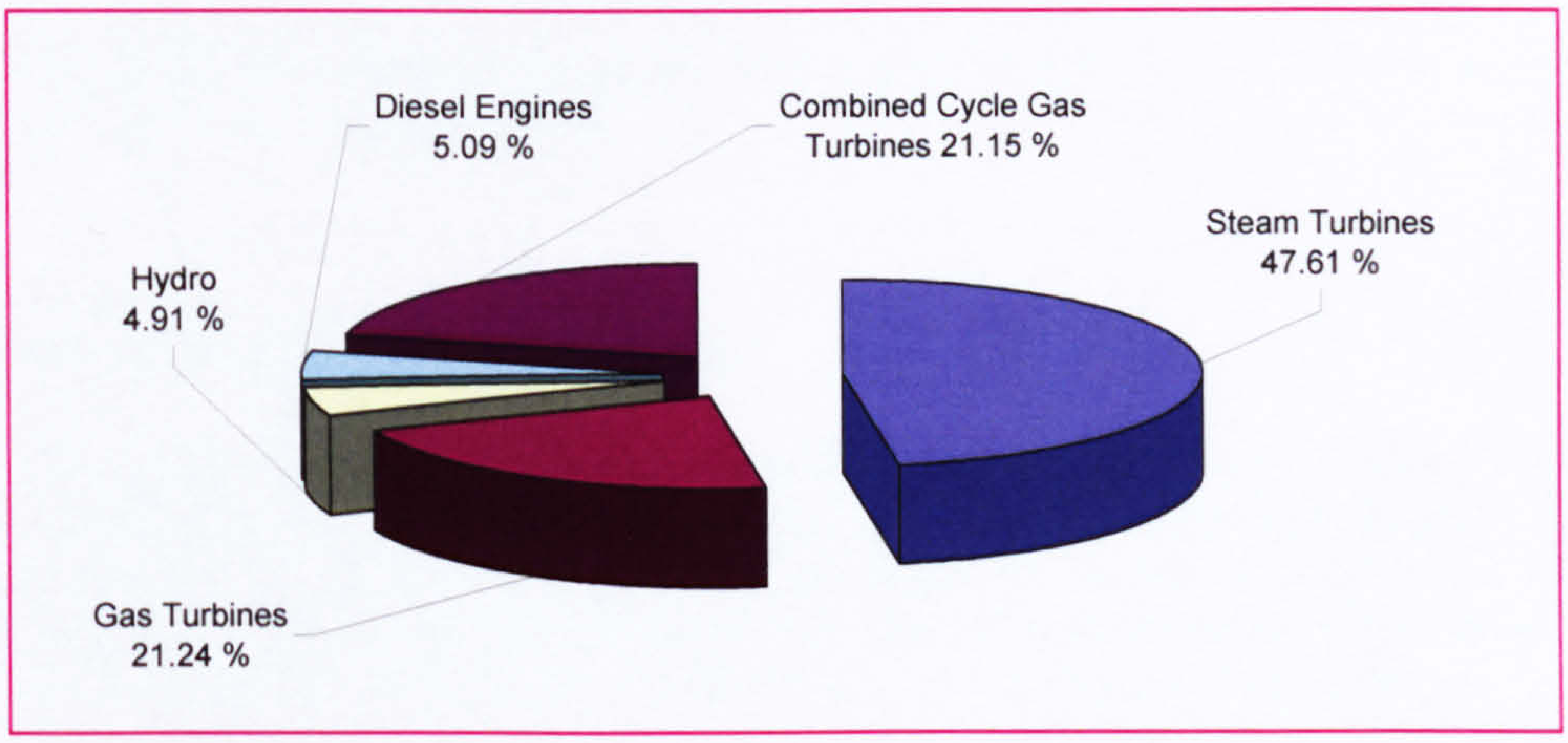
After the emergence of Bangladesh as an independent state, on the 16 December in 1971, BPDB was established in 1972 as a public organisation to boost the power sector with the responsibility for power generation, transmission and distribution of electricity throughout the country. During the 1970s, the GOB emphasized the importance of rural electrification for achieving a desirable social upliftment in the country. Organisational changes were made in the area of transmission and distribution of power in the country. In 1977, the Rural Electrification Board (REB) was created and in 1991 the government established the Dhaka Electric Supply Authority (DESA) to operate and develop the distribution system in and around Dhaka and bring about improvements in customer service, collection of revenue, and lessen the administrative burden on BPDB. To increase the efficiency of the distribution system and for better customer service, GOB implemented different reform programme. As a part of such programmes another two company the Power Grid Company of Bangladesh (PGCB) and the Dhaka Electric Supply Company (DESCO) were established in 1996 and 1997 respectively (BPDB, 2005). The distribution network area of DESA has been re-defined, with some area being allocated to DESCO for better management. On December 2002, all distribution networks were transferred to PGCB, the sole authority for operation, maintenance and extension of the distribution network of the country (MOF, 2005).

In order to develop the country's power sector, power generation and distribution was opened to both national and foreign private investments in 1996, followed by the formulation of 'Private Sector Power Generation Policy of Bangladesh' by the GOB. The involvement of Independent Power Producer (IPP) was made effective after October 1996. The country's first private power plant (with a 110 MW installed capacity) under private sector started contributing power to the national grid from October 1998 (MOF, 2005; BPDB, 2005).

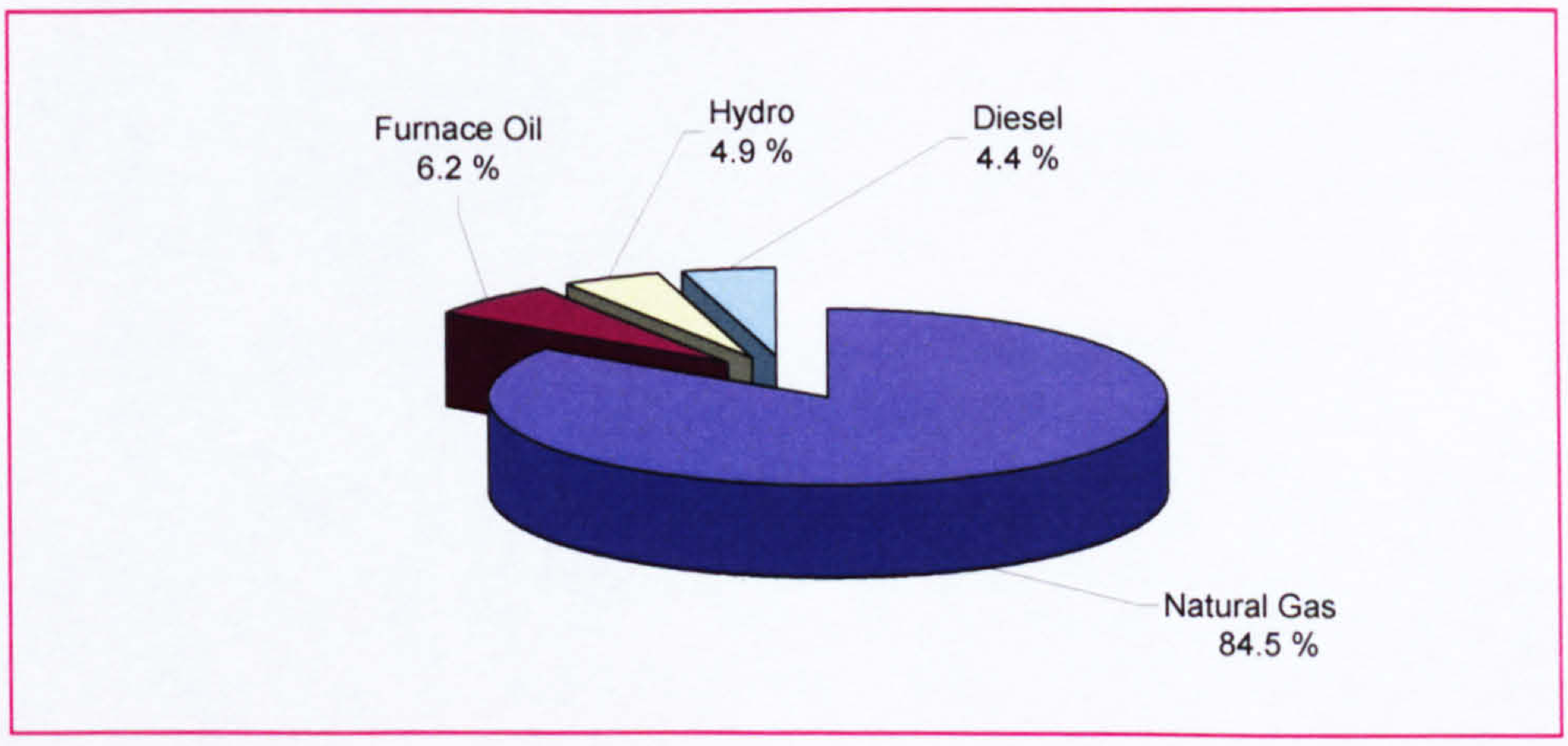
2.3.1 Electricity Generation

In 2003, the total installed electricity-generation capacity was 4.68 GW and firm generation capacity was 3.7 GW (BPDB, 2005). Different types of power plants generate electricity and synchronize it with the national grid. In addition, there are some isolated diesel-engine power stations at remote areas and islands. The distribution of the total installed capacity of both BPDB and IPP according to plant type and fuel type are shown in Figure 2.4. In 2003/2004, the total electricity generated was 20.061 TWh, of which 12.583 TWh was generated by the public sector (MOF, 2005). Per Capita electricity generation in 2002/2003 and 2003/2004 were 144 kWh and 154 kWh respectively (MOF, 2005).

The Jamuna-Padma-Meghna river system divides Bangladesh into two parts; east and west (see Figure 2.1). All natural gas fields are situated in the eastern part of the country. In this part, electricity is generated in gas-fired thermal power stations and a small percentage through hydropower. In the western part, imported liquid fuels are used for the generation of electricity. The fuel cost per kWh of the electricity generated in the western part is much higher than that in the eastern part. Low cost electricity, generated in the eastern part, is transferred to the western part through the 230 kV East-West Inter-connector transmission line. BPDB owns and operate the high voltage transmission network throughout Bangladesh. The transmission network is 5,976 km long, comprising 230 and 132 kV line. The total numbers of grid sub-stations in the country are 72, 10 of them are 230 kV and 62 are 132 kV, with a total capacity of 8,827 MVA (BPDB, 2005).



(a) According to plant type



(b) According to fuel type

Figure 2.4 Installed Capacity of power plants in 2003 (BPDB, 2005)

Electricity generated from different power stations is distributed by BPDB, DESA, DESCO and REB. BPDB is responsible for the distribution of electricity in most areas of the country except Dhaka City and some rural areas. DESA and DESCO are responsible for distribution of electricity in Dhaka city, whereas REB is responsible for the remaining rural areas.

2.3.2 Electricity Consumption

Industrial and domestic sectors are the main consumers of the electricity (BPBD, 2005). Some industries (both small and large) in Bangladesh generate their own power. Commonly, gas engines are used for this purpose. Only 20% of the population (25% in urban areas and 10% in rural areas) are connected to grid electricity, with the vast majority (i.e. 80%) being deprived of conventional electricity (EIA, 2004). With 80% of the total population of the country residing in rural areas, rural electrification is very important for the overall economic development of Bangladesh. REB has been supplying electricity to rural areas through a number of Rural Electrification Societies, known as 'Polly Biddut Samity' (PBS). As on June 2004, 67 of these were operating commercially in the country. There are 53,94,736 customers, in 41,125 villages. This required the installation of distribution lines with a total length of 1,73,125 km and 328, 33/11 kV grid substations (REB, 2004).

2.4 Renewable Energy Utilisation

In the context of Bangladesh, the main renewable energy resources are solar energy, biomass and wind power. There is some potential of mini/micro hydropower, which could meet some of the local needs of electricity. No major studies have been undertaken to explore the potential of tidal, wave and ocean thermal energy resources. In Bangladesh, many academic institutions, government departments, non-governmental organisation and private companies, such as BPDB, REB, Dhaka University (DU), Bangladesh Institute of Technology (BIT), Bangladesh University of Engineering and Technology (BUET), Bangladesh Atomic Energy Commission (BAEC), Local Government Engineering Department (LGED), Bangladesh Centre for Advanced studies (BCAS), Bangladesh Council of Scientific and Industrial Research (BCSIR), Bangladesh Rice Research Institute (BRRI), Bangladesh Rural Advancement Committee (BRAC), Rahim Afroaz and Grameen Shakti (GS) are involved in R&D programme related to renewable energy technologies.

The geographical location of Bangladesh is ideal for tapping solar energy effectively. Solar photovoltaic (PV) systems are gaining acceptability as a technology for electricity generation in remote and rural areas. Recently, there have been three substantial PV installations in Bangladesh for rural electrification. These are the REB 62 kW_p solar electrification project in 4 isolated islands in the Narshingdi district; the Grameen Shakti and BRAC projects, where 42,000 and 10,456 numbers of small solar PV systems has been installed respectively in rural households (REIN, 2005b). A number of solar thermal heating systems have also been developed and fabricated in the country for research, development and demonstration purposes.

Biomass, unlike other renewable resources, is a versatile source of energy. It can be used as a solid fuel or converted into liquid or gaseous fuels. Biomass-to-power technologies convert biomass fuels to heat and electricity using equipment similar to that used with fossil fuels. An agriculture-based country like Bangladesh has huge biomass resources. It is estimated that in Bangladesh, biomass (mainly agricultural residues, fuel wood and animal waste) satisfies 60% share in total energy consumption of the country (REIN, 2005e). 29.7 billion m^3/day of biogas can be generated from the 220 million kg/day cattle dung produced by 22 million cattle heads, 0.525 million m^3/day can be generated from poultry litter and 0.058 million m^3/day can be generated from water hyacinth (Sarkar et al. 1999). LGED and BCSIR installed biogas plants in different parts of the country. Small scale biomass-to-electricity generation plants have been installed in the country. Annual amount of biomass generation, consumption and its availability for electricity generation is yet to be estimated.

Wind mapping for the country is yet to be completed. Study reveals that enormous prospect for harnessing power from the wind exists in the coastal regions of the country (Sarkar et al. 1999). Hybrid generation of electricity, using other energy sources as complementary to wind energy, has now been given some attention. This could be suitable for localised small grid systems or battery charging, especially in isolated areas with low wind regimes. A 10 MW wind power electricity generating project is being implementing by BPDB at Muhuri Dam, in the Feni district (REIN, 2005c).

The only hydroelectric power plant in the country is the 230 MW Kaptai Dam operated by BPDB. Several studies have been carried out by LGED, BPDB and Bangladesh Water Development Board (BWDB) to assess the potential and viability of small hydro-power utilisation in the country (REIN, 2005d).

2.4.1 Wind Energy

Little systematic wind speed studies have been undertaken in the country. Bangladesh have a 724 km long coastline and many small islands (e.g. Saint Martin, Kutubdia, Swandip, and Hatia) in the Bay of Bengal, where strong south-westerly tradewind and sea-breeze prevail in the summer months and there is gentle north-easterly tradewind and land-breeze in the winter months.

Bangladesh Meteorological Department (BMD) is measuring wind speed at different locations in the country at low heights for weather forecasting purposes, which is not sufficient for assessing the potential of harnessing wind power. A seasonal variation of wind speed prevails in the country, with a strong potential during April to September, and very weak potential during the rest of the year. Between June 1994 and June 1995, BMD measured wind speeds at a height of 20 m at Patenga in the Chittagong district, the most potential site for wind power harnessing in Bangladesh - see Table 2.3 (Sarkar et al. 1999).

More recently, different studies have been undertaken to assess the wind energy resource of the country. In one such project, BCAS in collaboration with LGED and the UK's Energy Technology Support Unit (ETSU) jointly established the Wind Energy Study (WEST). The study was financially supported by the British government and approved by Aid Management Office, Dhaka (AMOD) in September 1995. ETSU provided BCAS with the necessary technical assistance. LGED helped in the installation of the wind monitoring masts, and facilitated the collection and dispatch of data cards from the monitoring sites to BCAS headquarters at Dhaka on regular basis. After continuous measurement through 1996 and 1997 at 7 selected sites (see Figure 2.5), the final report was published in January 1998 - see Table 2.4 (REIN, 2005c).

Year	Month	Average wind speed (m/s)
1994	June	8.25
	July	7.81
	August	7.48
	September	6.93
	October	6.70
1995	January	6.43
	February	6.45
	March	7.37
	April	7.92
	May	8.47
	June 1-10	8.69

Table 2.3 Wind speed at Patenga (at 20m height) (Sarkar et al. 1999)

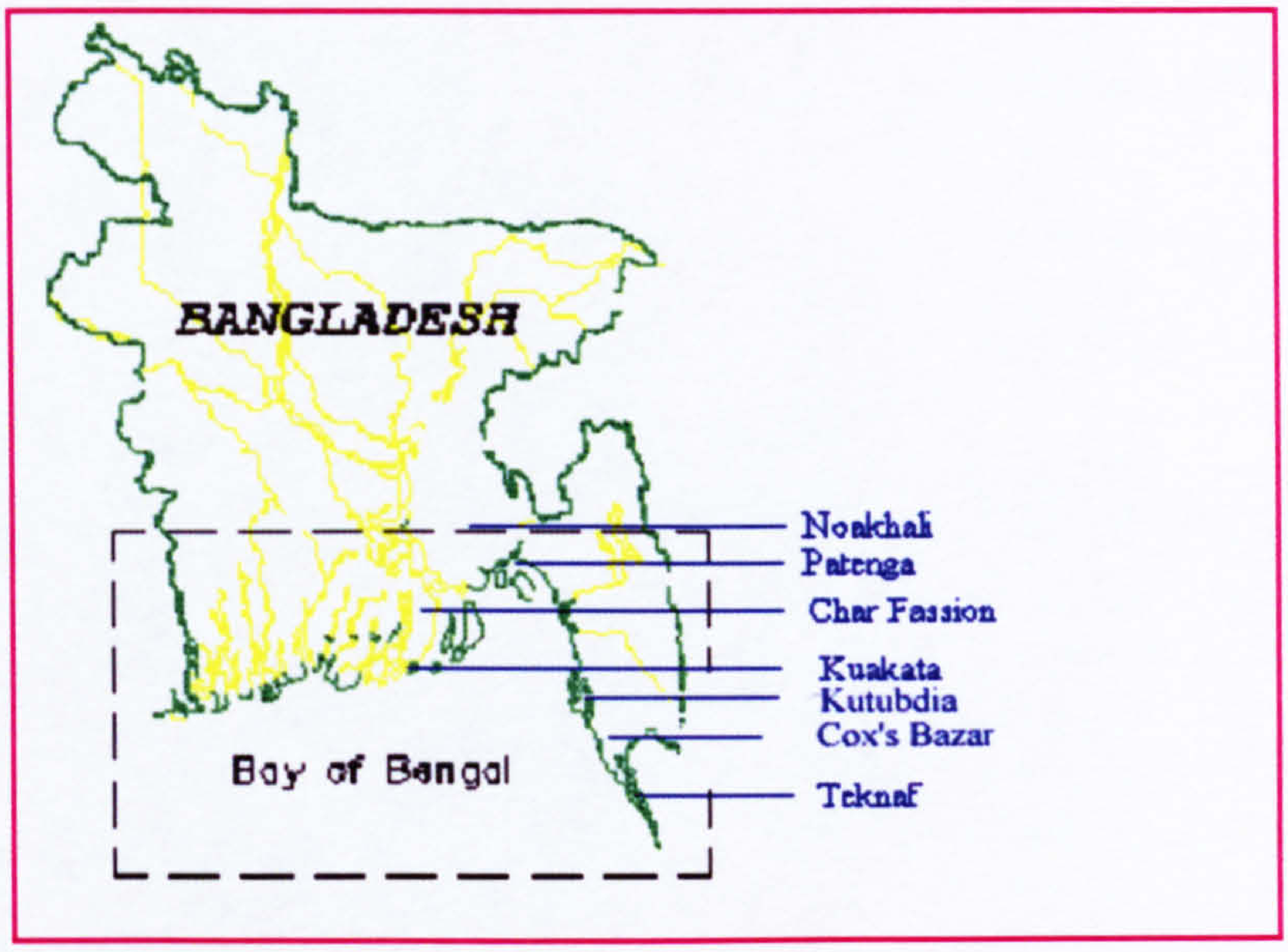


Figure 2.5 Coastal regions: prospective area for wind energy utilization

Table 2.4 shows that the average annual wind speed measured in 7 coastal stations range from 2.94 m/sec to 4.52 m/sec. The WEST study provides useful and important information. The final report recommended the following wind-energy utlisation R&D schemes (Islam, 2002b):

- A pilot wind turbine plant may be set up and be linked with the existing 250 kW diesel power station of BPDB at Kutubdia, to study the overall performance of a hybrid wind-diesel system in an isolated local grid.
- A demonstration wind power generating plant at Kuakata may be set up and connected to the existing grid to study the performance of such a system.
- A study may be undertaken to asses the performance of wind pumps for lifting water for drinking and crop irrigation at Kutubdia island.
- The present wind map of the country may be updated by joint efforts of the BMD and other interested groups, to estimate the wind energy potential.

GTZ of Germany in collaboration with REB of Bangladesh also conducted a parallel study. Wind speeds at Patenga, at a height of 20m are shown in Table 2.5. Wind speed measurements by WEST (see Table 2.4) and GTZ (see Table 2.5) confirmed that wind speeds are much higher in summer months (due to monsoon wind) than in winter months.

For estimating the wind energy potential, long-term systematic wind speeds data is required. Under the Sustainable Rural Energy (SRE) programme, LGED in collaboration with BUET and BIT Chittagong, has started Wind Energy Resource Mapping (WERM) project. The study aims at assessing wind energy potential of the country by systematic observation of wind regimes in initially 20 different suitable locations, including the Chittagonj Hill Tracts region, over a longer period of time (Islam, 2002b; REIN, 2005c).

Year	Month	Monthly – average wind speed (in m/s) at the monitoring stations						
		Patenga	Cox's Bazaar	Teknaf	Noakhali	Char Fassion[a]	Kua-kata	Kutubdia
1996	June	8.75	-	-	-	-	-	-
	July	5.87	5.42	5.77	-	-	-	-
	August	5.32	5.33	4.90	4.70	5.20 (4.60)	5.70	-
	September	3.36	3.69	3.46	2.94	3.34 (2.80)	3.77	3.58
	October	3.20	3.74	3.30	2.83	3.70 (3.07)	2.18	3.98
	November	2.61	2.93	2.29	1.91	-	1.98	3.23
	December	2.97	1.78	1.44	1.35	3.09 (2.38)	3.35	3.38
1997	January	3.25	2.33	1.99	1.31	2.80 (2.19)	3.18	3.67
	February	2.66	1.99	1.90	1.90	2.69 (2.02)	3.37	3.29
	March	3.13	2.42	2.26	2.38	3.54 (3.09)	4.84	3.53
	April	2.88	1.84	1.65	2.25	3.29 (2.28)	4.93	3.11
	May	4.96	3.97	3.09	3.99	4.81 (3.71)	6.28	4.89
	June	5.83	4.64	3.26	5.00	5.76 (4.42)	7.31	5.90
	July	5.67	4.80	4.33	4.92	5.22 (3.94)	7.34	6.17
	August	5.13	4.31	4.03	3.85	5.17 (4.01)	-	5.34
	September	-	2.96	1.83	2.77	3.08 (2.20)	-	3.97
Annual average		3.95	3.34	2.94	2.96	4.07 (3.21)	4.52	4.21

[a] values between brackets represent corresponding values measured at 10 m height

Table 2.4 Monthly average wind speeds at 25 m height at 7 coastal stations measured by WEST (REIN, 2005c)

Month	Year	
	1995	1996
January	-	-
February	-	-
March	6.7	-
April	7.2	-
May	7.7	8.0
June	8.1	6.9
July	8.0	8.4
August	7.4	3.5
September	6.8	3.9
October	6.2	3.2
November	4.4	2.6
December	4.2	2.2

Table 2.5 Monthly average wind-speeds (m/s) at Patenga measured by GTZ (Islam, 2002b)

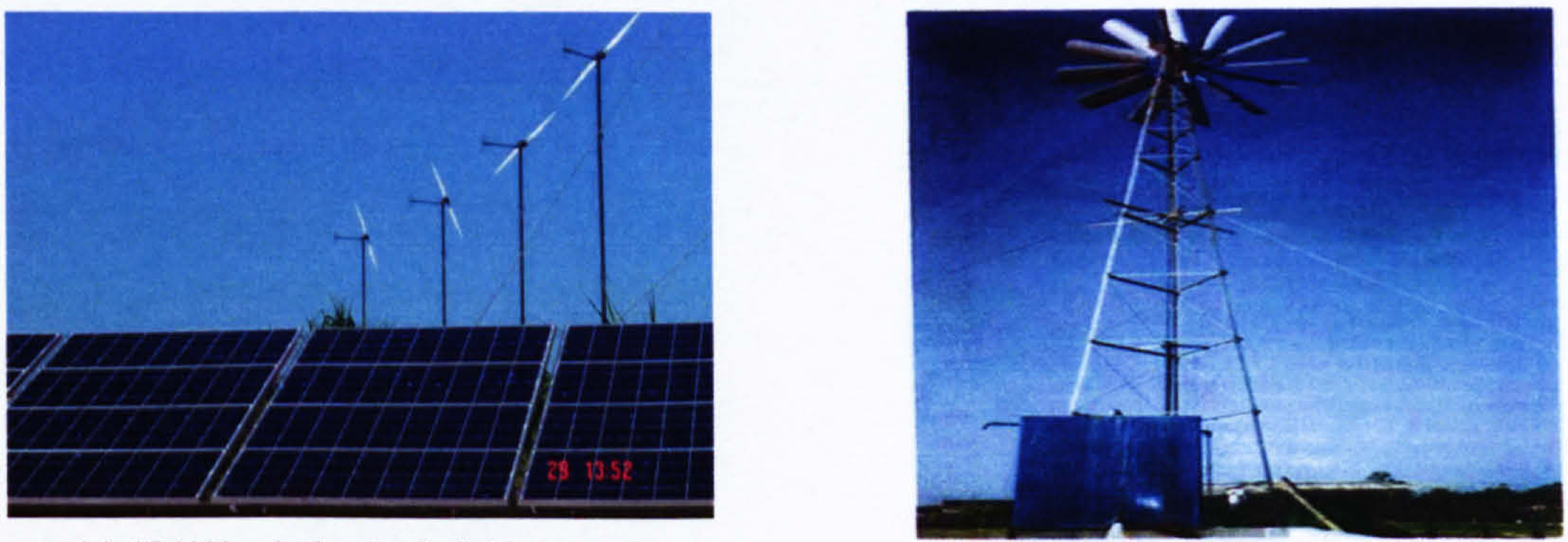
2.4.1.1 Present Application

BPDB is being implementing a 10 MW grid connected wind energy-based electricity generating plant at Muhuri Dam, in the Feni district. Also, the installation of 0.90 MW pilot scale grid connected wind energy-based electricity generating plant is being planned by BPDB, at Moghnama Ghat in the Cox's Bazar district (REIN, 2005c; BPDB, 2005).

Small-scale wind turbine-generators have been installed by GS and BRAC in the coastal regions of the country. GS installed 2 such types at Chakoria in the Chittagong district: 300 W unit from Southeast Air Module, USA and 1 kW unit from LMW, the Netherlands. BRAC installed 11 wind turbine-generators in various coastal sites. These are DC operation type systems supplying power to some target groups to improve their standard of living (Hossain, 2005).

Due to seasonal variation of wind speed, wind power generation and its application has certain limit. However, most of potential sites for wind power harnessing in Bangladesh are situated in coastal regions, which are generally not connected to the national grid. So, wind-solar-diesel or wind-diesel hybrid power generators are more useful in these regions. 4 hybrid power stations (combination of wind turbines, diesel generator and solar PV) have been installed by GS in the coastal areas of the Barguna district. Three of these have a capacity of 1.5 kW while the fourth has a capacity of 10 kW (GS, 2001). Under the SRE programme, LGED installed 10 KW_p wind-solar hybrid systems at St. Martins island (an island in the Bay of Bengal in the Chittagong district) – see Figure 2.6 (a). This is largest hybrid project in the country and was financed by UNDP. The generated electricity from the hybrid system is supplied to the hotels, markets and laboratory (REIN, 2005c).

LGED and BCAS have been working on assessing the viability of wind pump in Bangladesh. LGED installed a number of wind pumps, with a tower height of 8.4 m, at a different location, including Tangail, Kustia and Cox's Bazar districts (REIN, 2005c). Each of these indigenously manufactured wind pumps has a theoretical power output of 385 W at a wind speed of 4 m/s. BCAS installed a wind pump designed by the Intermediate Technology (IT) Group of the UK and manufactured in Pakistan (Hossain, 2005). The wind pump was located in an agricultural field at Patenga in the Chittagong district. The tower height is 12.5 m and the rotor has 12 blades - see Figure 2.6 (b).



(a) 10 kW_e wind-solar hybrid power system in St. Martin Island

(b) A wind pump set installed by BCAS at Patenga, Chittagong

Figure 2.6 Wind energy utilisation in Bangladesh

Daily water delivery has been found to vary, and the average daily water output between November and January was about 8 m^3. It appears that suitably designed wind pumps can be extensively used for irrigation of vegetables in winter months in the coastal region. Also it is possible to utilise them to draw underground fresh water for drinking purposes in coastal islands (Hossain, 2005).

2.4.2 Solar Energy

Bangladesh is ideally located for tapping solar energy effectively. Daily solar radiation varies from 3 to 6 kWh/m^2. Maximum solar radiation is available during March-April and minimum radiation occurs during December-January. Solar radiation data in Dhaka City is shown in Figure 2.7. Being largely a flat country, this data may be taken as representative of the whole of Bangladesh (Sarkar et al. 1999). Monthly average solar radiation in different divisions, reported by CES (2005), is shown in Table 2.6. Solar thermal energy has traditionally been utilised in households and industrial activities in Bangladesh since early days (e.g. drying of crops and fish and production of salt from sea-water).

Currently, BUET, BAEC, BCSIR, DU, BPDB, GS, BRAC, REB, and a few other organisations are continuing their research to improve the performances of solar energy utilisation systems and expand their use to new application areas (e.g. solar water heaters and solar cookers).

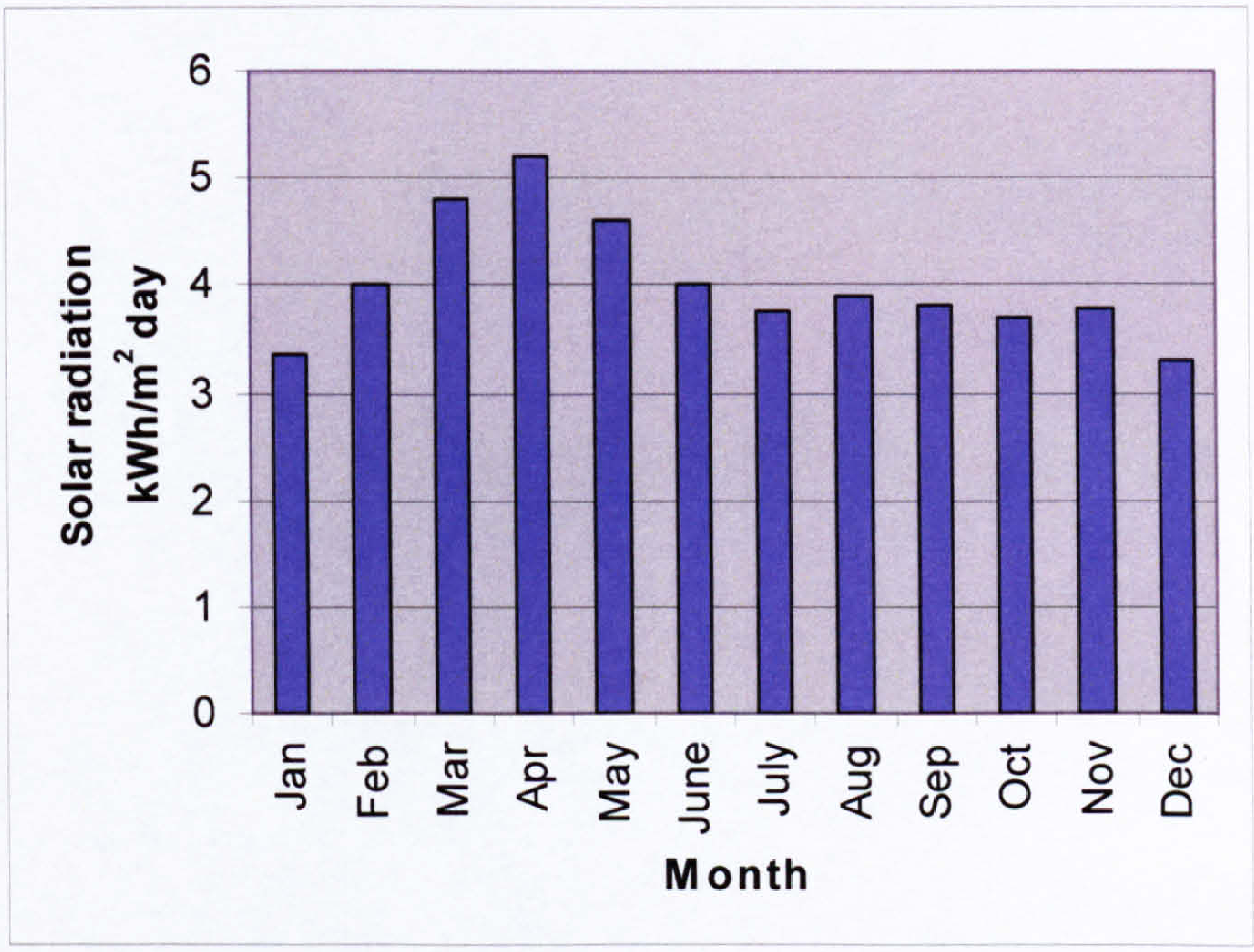


Figure 2.7 Monthly average daily solar radiations for Dhaka city (Sarkar et al. 1999)

Month	Monthly average daily radiation (in kWh/m^2) at the stated division					
	Dhaka	Rajshahi	Sylhet	Bogra	Barishal	Jessor
January	4.03	3.96	4.00	4.01	4.17	4.25
February	4.78	4.47	4.63	4.69	4.81	4.85
March	5.33	5.88	5.2	5.68	5.30	4.50
April	5.71	6.24	5.24	5.87	5.94	6.23
May	5.71	6.17	5.37	6.02	5.75	6.09
June	4.80	5.25	4.53	5.26	4.39	5.12
July	4.41	4.79	4.14	4.34	4.2	4.81
August	4.82	5.16	4.56	4.84	4.42	4.93
September	4.41	4.96	4.07	4.67	4.48	4.57
October	4.61	4.88	4.61	4.65	4.71	4.68
November	4.27	4.42	4.32	4.35	4.35	4.24
December	3.92	3.82	3.85	3.87	3.95	3.97
Annual Average	**4.73**	**5.00**	**4.54**	**4.85**	**4.71**	**4.85**

Table 2.6 Monthly average daily solar radiation recorded at different divisions of Bangladesh from 1988 to 1998 (CES, 2005)

In Bangladesh, PV power systems are being accepted gradually, but the slow progress achieved is due to their high initial capital cost. In 1981, BPDB installed 55 solar powered warning lights on 11 towers of the East-west Interconnector at Aricha in the Dhaka district (WEC, 2005). In 1983, to identify the marine routes at night, Bangladesh Inland Water Transport Authority (BIWTA) installed 125 solar-powered beacon lights (WEC, 2005). In 1988, BAEC installed the solar photovoltaic pilot project at Swandip Island (in the Bay of Bengal) for powering: beacon light on top of a watchtower; refrigerators in a veterinary hospital for storing life-saving vaccines; and a microphone and lighting in a local mosque (Islam, 2002a). Presently, BAEC is operating 2 solar PV water pumps: one at Savar in the Dhaka district; and another in the Moulovibazar district, to supply water in agricultural field. In these PV systems, there is no battery for storage of energy (Islam, 2002a).The Centre for Energy Studies (CES) of BUET is carrying out different studies on solar PV utilisation. Low-cost improved lanterns (capacity of 5/7.5/10 watt) for home lighting in rural areas is being designed and tested at the Renewable Energy Research Centre (RERC) of DU (REIN, 2005b).

2.4.2.1 Solar Thermal Systems

A variety of solar thermal systems have been developed and fabricated in the country, but these have not been commercialized. Examples of such systems include solar cookers, solar water heaters and solar dryers (Sarkar et al. 1999).

Solar cookers. Box type and parabolic reflector type solar cookers have been fabricated and tested in BCSIR and DU. Employing solar cookers is possible in Bangladesh for the 8 months of the year (i.e. October-May) when solar radiation is high. The remaining 4 months of the year (i.e. June-September) are often cloudy (Hussain et al. 1997). For cooking all over the year, an auxiliary fuel/energy source will be needed. In RERC of DU, a box type solar cooker has been developed where solar as well as electrical energy can be used as the source of energy. During bright sunshine hours the cooker is operated by solar energy and during the periods of low radiation intensity electricity of few watts is used as an auxiliary source (REIN, 2005b).

One parabolic reflector type solar cooker for a student hostel was designed and built by Institute of Fuel Research and Development (IFRD) of BCSIR. It has a 48 x 10^{-3} m^3 cooking pot and the surface area of the reflector is about 8 m^2 (Sarkar et al. 1999).

Solar dryers. The Institute of Food Science and Technology (IFST) of BCSIR has developed a 1.85 m x 0.6 m low cost cabinet type solar dryer. R&D works on solar dryers have been continuing at BAU, ANANDO, Bangladesh Rice Research Institute (BRRI) and at IFRD of BCSIR (WEC, 2005).

Solar water heaters. In Bangladesh, various types of solar water heating systems have been fabricated and tested for potential use in hospitals, hotels & industries. These systems can raise the water temperature in the range of 55^0-80^0C (REIN, 2005b). Different capacities of solar water heaters such as 500, 200 and 100 liter has been designed and built at RERC (REIN, 2005b). Design of such systems ranges from a simple earthen vat covered with polythene sheets to a sophisticated selectively-coated flat plate collector with double glazing of toughened glass. Flat plate thermal collectors have been designed and fabricated using copper as well as corrugated galvanized iron sheets at RERC of DU (REIN, 2005b).

2.4.2.2 Solar Photovoltaic Systems

Solar Photovoltaic is a proven viable option in remote areas of the country. Applications of solar PV in the country are: household electrification (e.g. Solar Home Systems), rural market electrification, health clinic electrification, street lighting, water pumping, micro enterprise (e.g. cellular phone service, tailoring shop) electrification and remote telecommunication. Solar Home Systems (SHS) are gaining popularity in the country. Example's of solar PV systems installed in Bangladesh is shown in Table 2.7.

Name of organisation	Type and number of solar PV systems and locations	Total installed electrical capacity (kW)
GS	42,000 SHSs, installed all over the country	2150
BRAC	10,456 SHSs, installed all over the country	300.545 Capacity: 40 W (20%), 50 W (60%) and 75 W (20%)
BPDB	300 SHSs at Juraichari, in the Rangamati district	54
LGED	In different coastal areas	19.6
SRE Programme of UNDP	-	33.8
BCSIR	82 SHS's	1.5
REB	SHSs installed in the Narshingdi district	62
Thengamara Mohila Sabuj Sangha (TMSS)	762 SHSs	Capacity: 30/40/50/75 W
CMES	618 SHSs	2.85
UBOMUS	400 SHSs	
COAST Trust	352 SHSs	-
Integrated Development Foundation	601 SHSs	-
Srizony Bangladesh	1,710 SHSs	-
Shubashati	592 SHSs	-
Singer Bangladesh Ltd.	31 SHSs	-
Anando	SHSs installed in the khagrachari, Tangail and Cox's Bazar districts	3.75

Table 2.7 Utilisation of solar PV systems in Bangladesh (REIN, 2005b; BPDB, 2005)

Some of the important solar PV installations, installed in the country are:

- With a joined financing by the French and Bangladeshi Governments, 62 kW_e solar PV project was commissioned by REB in 1996/97, for the electrification of rural households and commercial enterprises in the 4 islands (Karimpur, Natunbazar, Alipur and Panchabati) of the Narshingdi district (REB, 2004). It is the single biggest solar PV project installed in the country. The project covered an area of 29 km^2 with about 8,500 households in 21 villages. FONDEM of France carried out the initial design, and selected the site, based on a socio-economic study and site survey conducted by BCAS. Apex Inginierie of France supplied the solar modules and equipment. ARMCO, a Bangladeshi engineering firm installed the entire system. A total of 795 PV systems of 5 variants (i.e. I to V), ranging in output from 6 W_e to 92 W_e, were supplied/installed. These PV systems are divided into 2 broad categories: stand-alone systems and charging station-based systems (REB, 2004). In the stand-alone systems, the users are provided with all the components, i.e. PV modules, storage battery, controller, wiring and the loads (e.g. lanterns, lamps, TVs, fans and refrigerators). In the charging station-based systems, all the components, with the exception of the PV module, are provided to the users. This pilot project attracted the attention of a large number of international donor agencies (e.g. the World Bank, ADB, GEF, USAID, and CIDA) and has acted as a flagship venture in encouraging the promotion of solar PV and other renewable energy projects by public, private and NGO institutions and organisations.

- LGED has successfully completed the solar electrification of a market at Ganguita, in the Jhenaidah district. This project has been undertaken under the SRE programme of UNDP and implemented by LGED. The site has been selected for solar electrification because of its remote location (about 7 km away from the nearest grid connection), where a 5 kW diesel generator was used and operated previously by a private entrepreneur. This is the first centralised solar PV system in Bangladesh. The PV system has the capacity to produce 1.8 kW_e with daily energy output of 2 kWh, providing electricity to 45 shops, 3 small food processing facilities, one health centre and one bazaar mosque (REIN, 2005b). The responsibility of operation and maintenance has been entrusted with a local NGO, Shuboshoti.

- The successful installation of the solar market electrification project represented a milestone for the green energy movement in the country. Another centralised 1.725 kW_e solar electrification project was implemented by LGED under the SRE programme at Nalitabari in the Sherpur district. It provides solar electricity to 60 houses of sheltering people, and has been operating smoothly (REIN, 2005b).

- Rahimafrooz Ltd., installed the following solar PV systems for rural applications (SDNBD, 2005b):
  - solar PV lanterns and vaccine refrigerators
  - small and medium stand alone systems (< 3 kW_e)
  - centralised solar PV power plant
  - railway signaling systems
  - telecommunication systems
  - navigation lightning systems

  One of these is the 1.2 kW_e solar PV system to provide electricity to the telephone exchanges in the coastal island of Char Fassion and Monpura in the Bhola district, with the financial assistance of the Government of Finland and Telegraph and Telephone Board of Bangladesh (SDNBD, 2005b).

- BPDB is being implementing a solar PV project in the remote areas of Chittagong Hill Tracts region, in three phases. The project consists of (BPDB, 2005):
  - 900 SHSs - each 120 W_e capacity
  - 30 sets of street light systems
  - sets of submersible water pumps - 50,000 liters/day/pump
  - 9 sets of vaccine refrigerators for the health clinics
  - sets of 10 kW_e centralised solar PV market electrification systems - for electrification of more than 200 shops in each market

  So far, the first phase of this project has been completed with the solar PV systems of - 300 SHSs, 10 street lights, 1 water pump, 2 vaccine refrigerators and one 10 kW centralised market electrification (BPDB, 2005).

2.4.3 Small Hydro-power

The only hydro-power plant of Bangladesh, has an installed capacity of 230 MW, comprising two 40 MW units and three 50 MW units. BPDB is considering a 100 MW capacity extension of this hydro-power plant (REIN, 2005d). The additional energy will be generated during the rainy season when most of the year's water is spilled.

World-wide small hydro-power projects become more popular for their cheapness, reliability and environmental friendliness. Bangladesh has carried out few investigations on its small hydropower resources. Small hydro projects will be economically viable if combined with an integrated project of flood control, irrigation and tourism. In 1984, six Chinese experts visited Bangladesh and identified 12 potential sites for small hydro-power generation. Out of these, only one site at Mahamaya Chara, in the Chittagong district, has been considered for development of an integrated project for flood control, irrigation and power generation (Islam, 2002b). A working group has been formed by the engineers of BPDB and BWDB to carryout groundwork of the project. The main objective of the project is to protect the land of about 10.5 km^2 from flood inundation during monsoon and to supply irrigation water during the dry season (REIN, 2005d; BPDB, 2005). A dam is thus proposed to be constructed on the Mahamaya Chara for this purpose. The reservoir water will be utilised for the generation of electricity by installing a water turbine at the foot of the dam.

A low cost 10 kW_e small hydro-power plant was installed by a local tribal man Mr. Aung Thuwi Khoin, at Monjaipara, in the Bandarban District. In this project, locally fabricated wooden turbine wheel was used. Generated electricity is being supplied to 40 households. Khoin's innovation of indigenous micro hydro-power unit attracted attention of LGED and UNDP (of Bangladesh). Later, LGED and Mr. Khoin carried out joint study and identified 8 potential sites for small hydro-power generation, in the southern hilly areas of Bangladesh (Islam, 2002b; REIN, 2005d).

Amongst these potential sites, Bamer Chara Irrigation Project - in Bashkhali thana of the Chittagong district, has been implemented by LGED, with an intention to provide irrigation facilities to 3.55 x 10^3 km^2 of land area. A large reservoir has been built to provide irrigation water during the dry season. Water enters the project area through a gated spillway and the downstream flow is controlled at by a conventional regulator. Currently LGED is examining the flow rate in the spillway and exploring the scope for installing a small hydro power plant at the site. It is estimated that the proposed site has the potential to generate 20 MW of electricity (REIN, 2005d). On the other hand, recently BPDB has submitted the proposal to the GOB for necessary approval, to implement the following two small hydro-power projects (BPDB, 2005):

- 10 kW hydro-power plant at Barkal in the Rangamati district
- 25 kW hydro-power plant at the Teesta Barrage

2.4.4 Biomass Energy

Biomass, as a replacement of fossil fuels, has been attracting attention from the viewpoint of CO_2 mitigation. If biomass is grown in a sustainable manner, its production and use creates no net accumulation of CO_2 in the atmosphere, because the CO_2 released during combustion is offset by the CO_2 bio-chemically fixed by photosynthesis (Yokoyama et al. 2000).

Rural population use biomass for domestic cooking, animal fodder and bedding, and as housing construction materials. Inefficient open-type stoves are commonly in use. These are fed either by dry tree leaves, fuel-wood, agro-wastes, rice-husk or cow-dung. At present, the efficiency of utilisation of biomass as an energy source is very low. The amount of biomass that can be saved through efficiency improvement can serve as a source of additional energy. Some affluent rural people also use kerosene stoves, locally constructed biogas plants, and small amounts of imported coal. IFRD of BCSIR has been developing and disseminating various models of improved stoves for the rural areas of Bangladesh (Banu, 1996). BCSIR distributed 0.2 million improved stoves all over the country. 70-80% of these stoves are functioning (REIN, 2005e). Many NGOs are working in providing technical and financial assistance to the poor rural people to have some efficient combustion system.

Briquetting of rice husk is a new and fast growing technology in Bangladesh. Briquettes are made without the use of a binder, through the application pressure and temperature usually in screw type machines. Biogas production has been practiced in the country since 1972. Cattle dung, Poultry droppings and water hyacinth are important resources which has potential use in biogas production (REIN, 2005e).

2.4.4.1 Briquetting of Biomass

Rice husk briquettes are being used in the commercial and industrial sectors as well as in households, creating a new use for the husk in the country. Briquetting started in the Sylhet district in early 1980's by the employment of 2 imported machines (Moral, 2000). Briquetting technology is expanding very quickly mainly in the north-eastern part of the country where fuel-wood is more abundant and the demand for husk is less. Briquettes produced in the north-east are transported to the western region where fuel wood is less available and the use of briquettes is still economic in spite of the extra cost of transportation. Successful tests for briquetting of saw dust, wood chips, bark, wood waste, charcoal, coffee husk, coconut fibres, sunflower husk, bagasse, municipal solid waste, straw, and cotton seed husk have also been carried out (Sarkar et al. 1999).

As a result of the proven technical and economic viability of the technology, a total of 906 biomass briquetting machines are currently in operation (Moral, 2000). Of these, 889 machines are locally made and only 17 are imported. The distribution of briquetting machines is shown in Table 2.8. Production capacity of these briquetting machines varies between 75 kg/hr and 150 kg/hr (Moral, 1999). The main problem encountered during the operation of the briquetting machines has been the rapid wear of the screws, which in some places technicians are addressing as best as they can with welding and grinding. BIT, Rajshahi has been conducting an extensive research on materials and energy efficiency of screw briquetting machines. It was found that heating the husk before feeding it to a briquetting screw is an effective way of reducing the electricity consumption as well as enhancing the screw life. 4 improved-design screw-type briquetting machines were fabricated by BIT for laboratory and field-testing. 2 machines were assembled in BIT laboratory for testing and demonstration purposes and other 2 were installed in a rural village to enhance the popularity of the technology as well as the products among the village people (Moral, 1999; Moral, 2000).

2.4.4.2 Biomass to Biogas

The production biogas by the anaerobic digestion of biomass has drawn government attention and a systematic development has been carried out in this field. The IFRD of BCSIR has been carrying out different pilot projects since 1973. The agencies involved in biogas technology in Bangladesh are: Agricultural Chemistry Department of BAU, Bangladesh Academy for Rural Development (BARD), IFRD of BCSIR, Bangladesh Small & Cottage Industries Corporation (BSCIC), Danish International Development Agency (DANIDA), LGED, Department of Environment (DOE) of Bangladesh, Department of Livestock (DLS), GS and some other NGOs.

District	**Number of briquetting machines**		
	Locally manufactured	Imported	Total
Sylhet	233	15	248
Khulna	100	2	102
Dinajpur	90	-	90
Chittagong	103	-	103
Rajshahi	60	-	60
Jessore	42	-	42
Kustia	32	-	32
Faridpur	24	-	24
Barishal	23	-	23
Patuakhali	9	-	9
Rangpur	54	-	54
Mymensing	16	-	16
Bogra	45	-	45
Comilla	21	-	21
Noakhali	11	-	11
Dhaka	4	-	4
Tangail	3	-	3
Pabna	19	-	19
Total	889	17	906

Table 2.8 Distribution of briquetting machines in Bangladesh (Moral, 1999)

Trends of the biogas technology in Bangladesh can be summarised as follows (Islam, 2002a; REIN, 2005e):

- The first floating-dome type biogas plant was demonstrated in 1972 at BAU, Mymensing. Later another plant, with a 6 m^3 digester volume was constructed to produce the gas requirements of a family of 6 members for lighting and cooking. In 1974, a biogas plant was constructed at BARD, Comilla. In 1976, IFRD constructed a family-size biogas plant at its campus.
- Around 1980, IFRD started to construct cheaper biogas plants. The experts of IFRD installed over 70 biogas plants for rich farmers at the owner's cost. With a view to speeding up the dissemination, the IFRD has introduced 2-week long training courses on construction, operation and maintenance of biogas plants. 60 nominees from BSCIC, Bangladesh Rural Development Board (BRDB), the World Bank (Bangladesh Branch) and NGOs have been trained.
- In 1981, Bangladesh DOE installed 110 plants of fixed-dome type and over 150 plants of floating-dome type under a government grant. 24 district-level officers of BSCIC were trained at the IFRD. After completing the training course, BSCIC installed a number of plants at the owner's cost. DANIDA temporarily supported the installation of few trench and bag-type digesters.
- In 1986, LGED constructed its first biogas plant at the Kurigram district. It also arranged a seminar there, which was attended by 300 engineers, scientists and interested persons from other districts.
- In 1992, IFRD in collaboration with Dhaka City Corporation constructed an experimental biogas plant of 85 m^3 digester volume at Dholpur in the Dhaka district for the treatment of the city garbage. Charged with of 52.5 tonnes of garbage, the plant produced an average of 60 m^3 biogas/day over period of 2 months and 40 tonnes of residue digestate, which is rich in plant nutrients (i.e. can be used as a biofertilizer).
- In 1993, LGED constructed its first water hyacinth digestion biogas plant in the Madaripur district. In 1994, LGED constructed its first poultry droppings digestion biogas plant from in the Dhaka district. It also installed MSW based biogas plants in 10 urban areas. By the end of 1994, LGED constructed about 200-biogas plants; out of which 8 were-floating dome type and the rests were fixed-dome type.
- Under the Fuel Saving Project of BCSIR, 161 plants were constructed through selected NGOs for farmers who paid a subsidized price. Recently BCSIR launched the biogas pilot plant project, financed by the GOB. Under this project a total 17,200 biogas plant has been installed in different areas of the country and 90% of these plants are functional. These plants are used for cooking, lighting and electricity generation.

Various types of biogas plants constructed by LGED are shown in Table 2.9. GS installed a number of bio-digester for producing biogas for cooking and for using residues in the field as an alternative to chemical fertilizer (REIN, 2005e). A 4 kW_e biogas generator has been installed by LGED at an orphanage institute in the Faridpur district. Biogas is produced from the poultry litre of 5000 poultry bird. There is a plan to increase the plant capacity to 10 kW_e, by increasing the poultry bird population to 20,000 (REIN, 2005e). BRAC installed 2 biogas generators, each 800 W_e capacity, at Shaturia and Shafipur in the Manikganj and Tangail districts respectively (REIN, 2005e). In both projects, cow manure was used for biogas production.

Biomass resources	Types of biogas plant	Rates of biogas production (m^3/day)	Number of biogas plants
Family type biogas plant:			
Cow manure	Fixed dome	3.40 - 4.25	700
Cow manure	Floating cover	3.40 - 4.25	6
	-	5.66 - 8.50	259
	-	11.04 - 12.18	55
	-	16.42 - 22.09	45
Human excreta	Fixed dome	3.96	5
	-	6.60	25
	-	10.59	27
	-	15.89	3
	-	22.65	1
	-	3.96	3
Water hyacinth	Fixed dome	9.91	2
MSW	Fixed dome	10.76	15
Poultry dropping	Fixed dome	11.89	20
Sub-total family type biogas plants			1166
Community type biogas plants:			
Human excreta	-	8.50	102
Human excreta	Fixed dome	7.08	20
Human excreta	-	11.33	2
Sub-total community type biogas plants			124
Total Biogas plants (Family and Community type)			1190

Table 2.9 Types of biogas plants installed by LGED (REIN, 2005e)

2.4.4.3 Gasification of Biomass in Bangladesh

BCSIR has designed and constructed an experimental down-draft gasifier for coconut-shell charcoal. Although charcoal produced from coconut shell is not a common product, it is estimated that over 80 ktonnes of coconut shell is available in the country annually (Sarkar et al. 1999). GS has installed a 10 kW_e gas engine-generator set based on a wood gasifier at Tetulia in the Panchagar district. The plant has been test run satisfactory both with cheap wood twigs, and even cheaper bamboo roots. Up to July 1999, GS provided 51 connections for supplying electricity to a neighbouring rural market and several households (GS, 2001).

2.5 Conclusions

Commercial primary energy resources of Bangladesh consist of the known reserves of natural gas and coal, and a limited hydro-electric capacity. Natural gas is the main commercial primary energy source of Bangladesh. The total estimated reserves of natural gas amount to 804.71 billion m^3, of which 580.78 billion m^3 is believed to be recoverable. In June 2004, the net recoverable gas reserve was estimated at only 423 billion m^3. Between 1992 and 1994, the total commercial primary energy consumption in Bangladesh increased at an average annual rate of 0.74 mtoe. The trend is mainly due the increased consumption of indigenous natural gas and imported oil. The contribution of hydropower to total commercial primary energy consumption is almost constant. In 2004, the total national commercial primary energy consumption was 16.8 mtoe. In this, the shares of natural gas, oil, coal and hydro-electricity were 70.8, 25, 2.4 and 1.8%, respectively. Power plants and fertilizer factories are the main users of the natural gas in the country, consuming 46.51 and 21.75% of the total, respectively.

In 2003/2004, the total electricity generated was 20.061 TWh, of which 12.583 TWh was generated by the public sector. During the same period, per capita electricity generation was 154 kWh. The distribution of the total installed capacity of 4.68 GW according to fuel types used are 84.5% natural gas, 6.2% furnace oil, 4.9% hydro and 4.4% diesel. Bangladesh has been facing a power crisis for about a decade, mainly because of inadequate power generation capacity compared with demand and the aging infrastructure of many existing power generation facilities. The World Bank has estimated that Bangladesh loses around US$1 billion per year due to power shortages and unreliable power supply (EIA, 2004). The Government of Bangladesh has a vision to electrify the whole of the country by the year 2020. Electricity supply to low-load rural and remote areas is characterised by high transmission and distribution costs and transmission losses, and heavily subsidised pricing.

The main renewable energy resources in Bangladesh are biomass, solar, wind and hydro-power. Hydro-power potential of Bangladesh is low due to the relative flatness of the country. Most of potential sites for wind power utilisation are situated in coastal regions. Wind power generation and its application in Bangladesh have certain limitations due to lack of reliable wind speed data and the remarkable seasonal variation of wind speed. The country has good prospects of utilising solar PV systems for electricity generation, but the high capital investment cost of solar PV is a big barrier for adopting such systems.

Biomass is a versatile source of energy; it can be used as a solid fuel or converted into liquid or gaseous fuels. Biomass is the major energy source in Bangladesh. Anaerobic digestion and gasification technologies have been installed and operated in the country. Biomass utilisation systems represent a proven option for small-to medium-scale decentralised electricity generation. Estimation of the national, division-wise and district-wise biomass availability is important for assessing the potential and economics of decentralised biomass electricity generation in Bangladesh.

CHAPTER 3

BIOMASS TO ELECTRICITY: CONVERSION TECHNOLOGIES

Biomass can be used to generate electricity, heat, liquid fuels for motor vehicles, or other alcohol fuels. In 1994, the total deployment of biomass electricity in the world was 127 TWh; and it is projected that in 2010, the deployment would be 291 TWh (Europa, 2005). Biomass-fuelled electricity generation is still marginal in developing regions, but it is projected to rise rapidly, nearly tripling from 10 TWh in 1995 to 27 TWh in 2020 (D'Apote, 2001). Accordingly, biomass consumption for power generation will also triple from 4 Mtoe to 12 Mtoe in 2020 (see Table 3.1). The technical concepts now being investigated for biomass electricity generation are as follows:

- Direct combustion of biomass and steam turbine or Stirling engine
- Co-firing of biomass with coal or natural gas and steam turbine
- Gasification of biomass and gas turbine or internal combustion engines
- Pyrolysis of biomass (to produce 'biocrude' liquid fuel) and internal combustion engines or gas turbines
- Anaerobic digestion of biomass and internal combustion engines or gas turbines
- Fermentation of biomass (to produce 'bio-ethanol' fuel) and internal combustion engines or gas turbines
- Fuel-cell

Electricity can be produced from biomass in a variety of plant sizes, which is useful for power generation for decentralized applications at the village level as well for supply to the national grids. Brief descriptions of each technology are presented in the following sections.

Country/ Region	Items	1995	2010	2020
China	Biomass used in power generation (Mtoe)	-	0.1	0.2
	Biomass-based power generation (TWh)	-	0.4	0.7
	% of total electricity generation	-	1.7	1.8
East-Asia	Biomass used in power generation (Mtoe)	0.3	0.7	1.7
	Biomass-based power generation (TWh)	0.3	0.6	1.5
	% of total electricity generation	0.0	0.0	0.1
South-Asia	Biomass used in power generation (Mtoe)	-	2.0	3.1
	Biomass-based power generation (TWh)	-	4.6	7.3
	% of total electricity generation	-	0.4	0.4
Latin America	Biomass used in power generation (Mtoe)	3.3	4.5	5.8
	Biomass-based power generation (TWh)	9.6	13.1	17.1
	% of total electricity generation	1.2	0.9	0.8
Africa	Biomass used in power generation (Mtoe)	0.4	0.8	0.8
	Biomass-based power generation (TWh)	0.3	0.6	0.6
	% of total electricity generation	0.1	0.1	0.1
Total developing countries	Biomass used in power generation (Mtoe)	4.0	8.1	11.7
	Biomass-based power generation (TWh)	10.2	19.3	27.1
	% of total electricity generation	0.3	0.3	0.3

Table 3.1 Biomass-based power generation in developing countries (D'Apote, 2001)

3.1 Direct Combustion of Biomass

The simplest method to generate electricity from biomass is to burn it, using air as the oxidant. The chemistry of complete oxidation of materials is:

$$C_xH_yO + O_2 \longrightarrow CO_2 + H_2O + \text{Heat}$$

An industrial biomass combustion system normally consists of fuel storage, feeding device, the combustor, ash removal device, heat recovery surface, flue gas cleaning facility and stack. Combustor design depends on the characteristics of biomass fuels.

3.1.1 Electricity Generation by Direct Combustion of Biomass

In principle, the energy system of biomass combustion is the same as that for fossil fuel combustion. Steam turbines and steam engines are used as proven technology to generate electricity through biomass combustion. Steam engines are available in the power range from approximately 50 kW_e to 1 MW_e, and steam turbines are available in the range of 0.5 MW_e up to 500 MW_e (IEA Bioenergy, 2003c). Units of these types are based on Rankine Steam Cycle. Biomass is burned in a boiler producing pressurized steam, which is expanded through a turbine to generate electricity (see Figure 3.1). Organic Rankine Cycle (ORC) using a thermal oil boiler instead of a costly steam boiler is also available in the range 0.5 MW to 2 MW (IEA Bioenergy, 2003c).

Steam engines can also be used for small-scale applications, enabling efficiencies of 6% - 10% in single-stage and 12% - 20% in multi-stage mode (IEA Bioenergy, 2003c). Externally fired Stirling engine is another way for small scale electricity generation by direct combustion of biomass. The heater of the Stirling engine is directly heated by the hot flue gas from the combustor. About 100 Stirling engines have been installed in India (Bhattacharya, 1993).

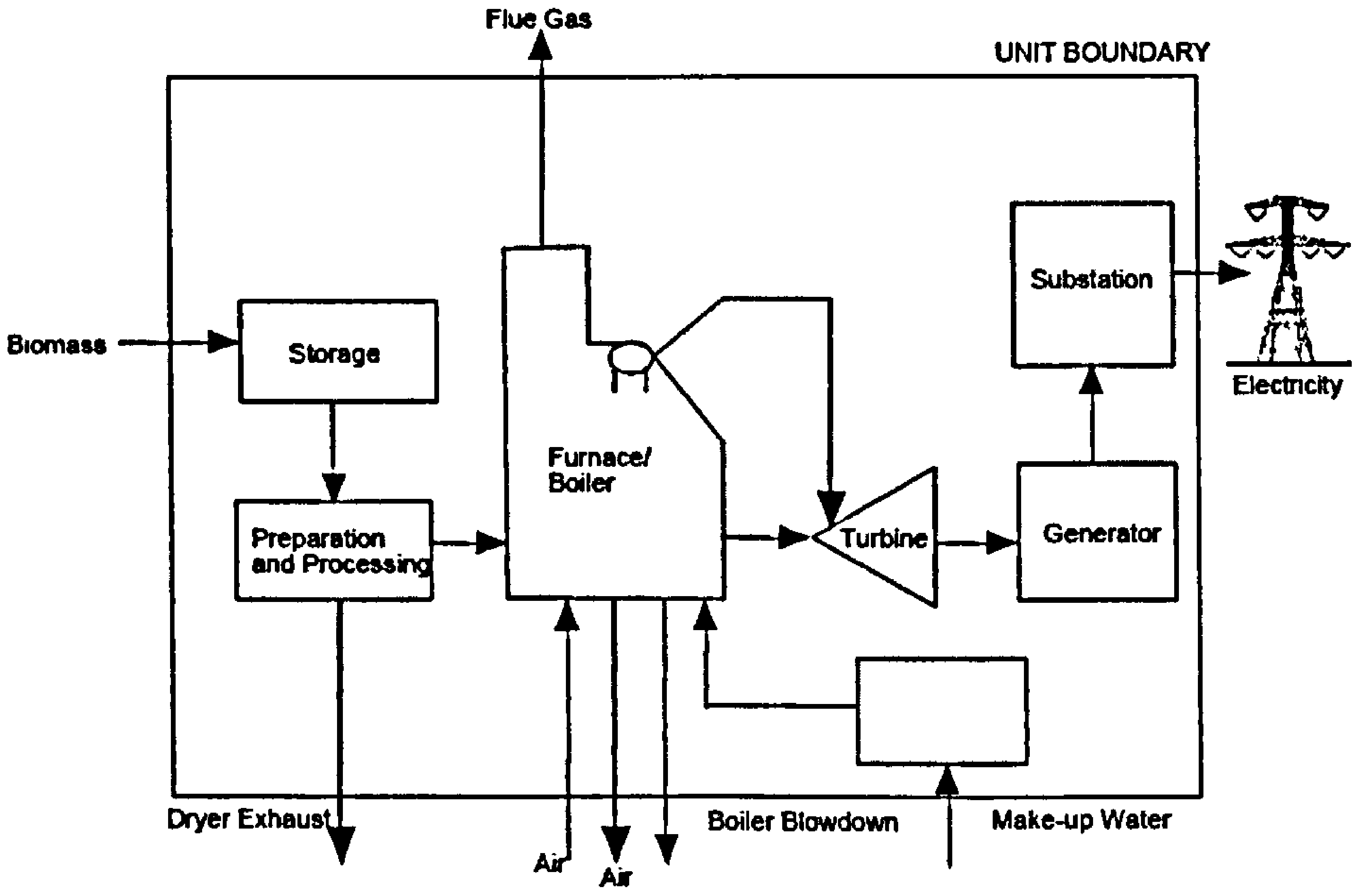


Figure 3.1 Schematic diagram of direct-fired biomass electricity generating system (EERE, 1999a)

3.2 Co-firing of Biomass

Co-firing of biomass in coal-fired plants and natural gas fired electricity generation plants is very promising technology. Co-firing of biomass in coal fired plants involves replacing a portion of the coal with biomass at an existing coal-fired power plant boiler. Table 3.2 shows the proximate and ultimate analyses of some biomass resources. Some physical and chemical properties of biomass residues (e.g. high MC, low bulk density, low melting point of ash and high volatile matter) complicate their processing for co-firing (Werther et al. 2000).

3.2.1 Options for Co-firing

The different options for co-firing of biomass are (Tillman, 2000):

- **Blending biomass with coal on the fuel pile.** It is the simple and least cost approach to blending biomass with coal. Some biomass can cause significant problems during blending of biomass with coal on the coal pile. For example, tree bark can be very stringy, and switch grass and straws when chopped to 25-50 mm in length can cause pluggage in the bunkers.
- **Co-firing with separate injection.** This method involves separately preparing the biomass, and then firing it in the boiler. This method involves more equipment than the first one, but can accomplish higher percentage co-firing in pulverized coal boilers.
- **Gasification-based co-firing.** In this type, biomass is first fed to a gasifier in order to generate producer gas. The gas is then fired in a boiler. It is the most capital-intensive approach to co-firing.

3.2.2 Electricity Generation by Co-firing of Biomass

Co-firing of biomass has been successfully demonstrated in the full range of coal boiler types, including pulverized coal boilers, stokers, and bubbling and circulating fluidized bed boilers (EERE, 1999b). For low level of co-firing up to 5-8% biomass, wood can be combined with coal prior to the pulverizer (Demirbas, 2003). For medium levels, 10-15% biomass, a separate wood preparation and delivery system should be provided with the boiler operation based on coal characteristics (Demirbas, 2003). For moderately high levels, 25-50% biomass, a multi-fuel system, such as a fluid bed, should be used and for above 50% biomass, a boiler designed specifically for biomass operation should be used (Demirbas, 2003).

Fuel	Proximate analysis (%)				Ultimate analysis (%)				
	Moisture	Volatile	FC[a]	Ash	C	H	O	N	S
Sunflower husk[b]	9.10	69.1	19.9	1.9	51.4	5.0	43.0	0.6	-
Cotton husk	6.90	73.0	16.9	3.2	50.4	8.4	39.8	1.4	-
Mustard husk	5.60	68.6	22.0	3.9	46.1	9.2	44.7	0.4	0.20
Soya husk	6.30	69.6	19.0	5.1	45.4	6.7	46.9	0.9	0.10
Groundnut shell	7.88	68.1	20.9	3.1	50.9	7.5	40.4	1.2	0.02
Coconut shell	4.40	70.5	22.0	3.1	51.2	5.6	43.1	0.0	0.10
Sewage sludge	6.90	44.6	7.0	41.5	52.0	6.3	32.1	6.3	3.10
Wood	40.00	46.7	12.8	0.5	50.7	5.9	43.1	0.2	0.04

a: fixed carbon; b: residues obtained during dry processing.

Table 3.2 Analysis of some agricultural and forest residues and coals (Werther et al. 2000)

In coal-fired suspension burners, the fuel has to be pre-treated in such a way that full combustion within the short residence time (i.e. 2-3 sec.) in the combustion chamber is realized. Lumpy biomass fuel, which has not been pre-treated, will need a longer time to burn out, depending on the size and moisture content. If the agricultural residue is in-homogeneous, the combustion process is difficult to control (Werther et al. 2000).

The combustion temperature of coal-fired boilers is 850-900°C for fluidized bed combustors and 1000-1200°C for suspension burners. The melting points of ashes of agricultural residue are often lower which could lead to slugging or fouling (Werther et al. 2000). Ash from coal combustor is often used as inert material in the cement industry. The co-firing of agricultural waste changes the composition of the ash, which may hinder its utilization in the cement industry (Werther et al. 2000).

3.3 Gasification of Biomass

Gasification is a technique to convert a solid fuel into a gaseous fuel in the presence of hot steam and limited amount of air or oxygen. The resulting gas (i.e. producer gas) obtained by a gasification process is a mixture whose main constituents are CO, H_2, and CH_4 together with CO_2 and N_2. The energy content of the producer gas is 3 – 5 MJ/m^3 (Larkin et al. 2004).

3.3.1 Electricity Generation by Gasification of Biomass

Gasification offers the advantages of feedstock flexibity and environmentally friendly technology for low-cost electricity production, compared to combustion technology (Stiegel and Maxwell, 2001). Gasification systems may be either direct or indirect. In direct gasifier systems, pyrolysis, gasification and combustion take place in one vessel; whereas in indirect gasification type, pyrolysis and gasification occur in one vessel, and char combustion takes place in a separate vessel (see Figure 3.2). In direct gasification, air and sometimes steam are introduced directly to the single gasifier vessel. In indirect gasification, an inert-heat transfer medium, such as sand, carries heat generated in the combustor to the gasifier to drive the pyrolysis and char gasification reactions (EERE, 1999c).

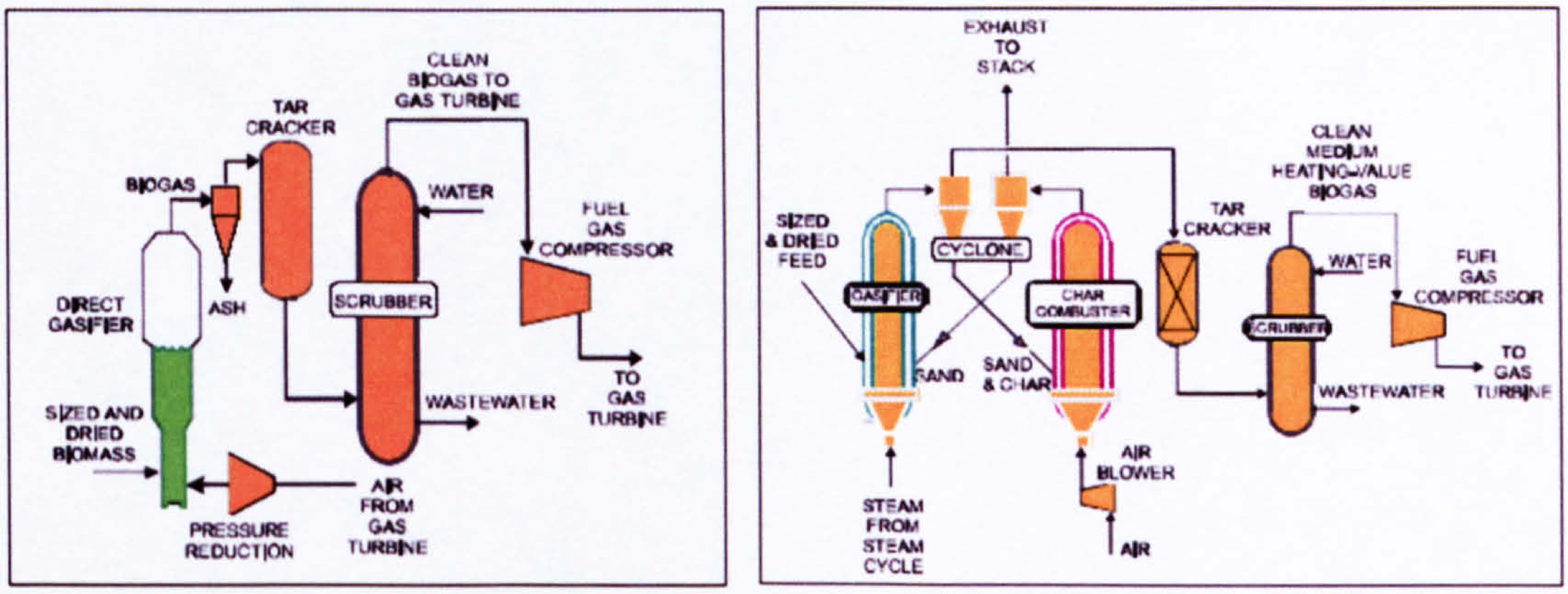


Figure 3.2 Direct and indirect low pressure gasifiers (EERE, 1999c)

There are two ways of generating electricity by using the product gases – either using the internal combustion engines or gas turbines. The gasifier produces a low heat value producer gas with low tar and dust contents. The gas is further cleaned, using cooling and cleaning train. Cleaned gas is used to drive an ICE along with diesel. In India, technological advancement has been achieved in gasification of woody and non-woody biomass up to the MW level (Singh, 1998).

The options for generating electricity using gas turbines are:

- simple cycle gas turbine
- steam-injected gas turbine (SIGT)
- inter-cooled steam-injected gas turbine (ISIGT) and
- combined cycle gas turbine (CCGT)

The combined-cycle is the most energy efficient power generating cycle (Williams and Larson, 1996). Pilot demonstration plants using fuel wood or sugarcane bagasee fuel, with electrical outputs in the 5 – 10 MW range are being tested (Larkin et al. 2004). Schematic diagram of a high-pressure direct biomass gasifier combined cycle is shown in Figure 3.3. The main disadvantage of this plant is the need for a cleanup system for the control of corrosive gas phase compounds such as tar, acid gas and alkali metals (Belgiorno et al. 2003).

3.4 Pyrolysis of Biomass

Pyrolysis is a biomass conversion technique, through which biomass is converted to liquid (bio-oil or bio-crude), solid and gaseous fractions by heating the biomass in the absence of air or oxygen. Depending on the operating conditions, there are three types of pyrolysis process: conventional pyrolysis, fast pyrolysis and flash pyrolysis (Maschio et al. 1992).

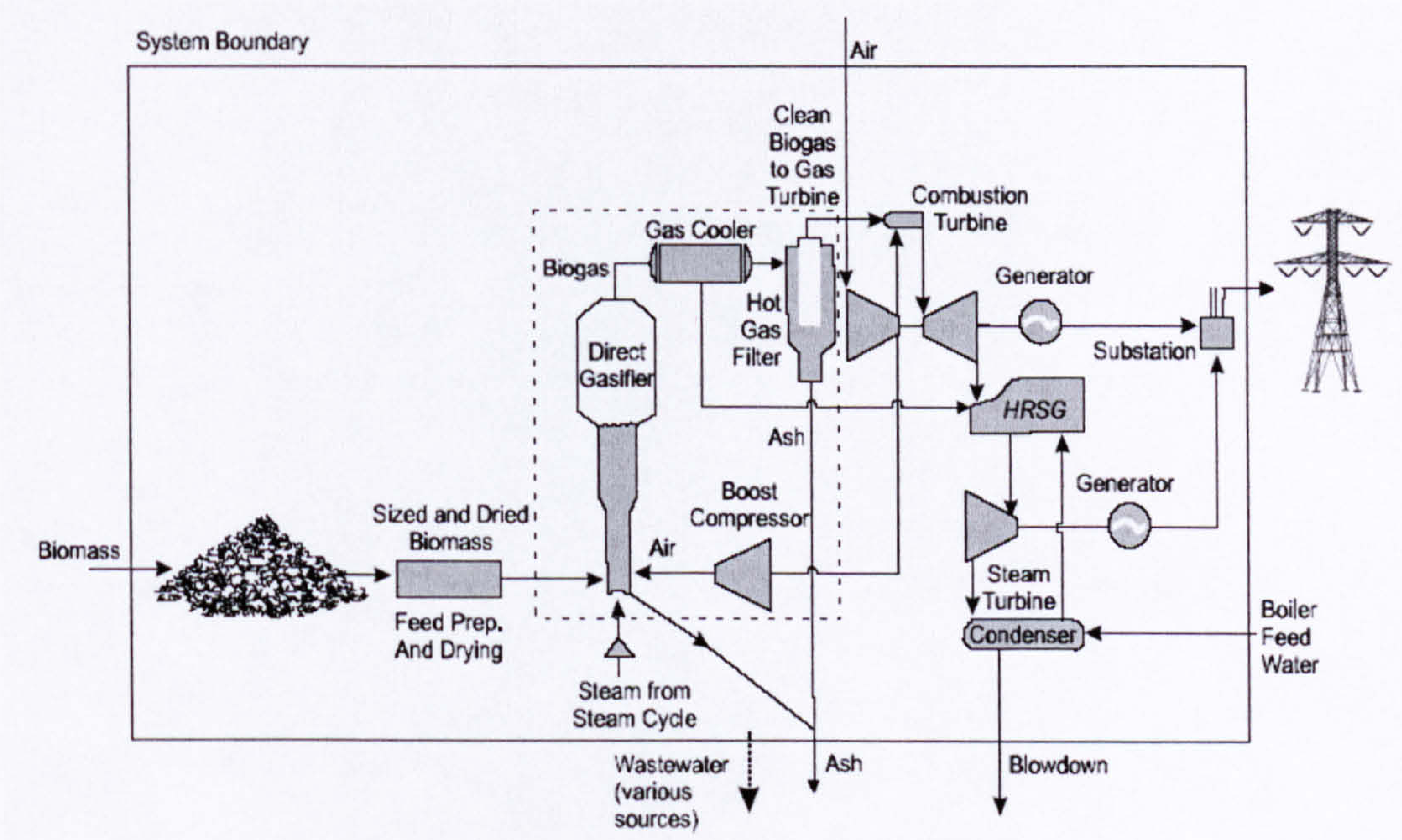


Figure 3.3 Biomass gasification combined cycle gas turbine system (EERE, 1999c)

Conventional pyrolysis occurs under a slow heating rate. This condition permits the production of solid, liquid or gaseous pyrolysis products in significant proportions. Fast pyrolysis can directly produce a liquid fuel from biomass, which can be readily stored or transported. Flash pyrolysis occurs under a fast heating rate with very low (<0.5 s) solid residence time. Different operating parameters of the above types of pyrolysis are summarized in Table 3.3. Fast pyrolysis is now an acceptable feasible and viable route to renewable liquid fuels (Bridgwater and Peacocke, 2000).

3.4.1 Fast Pyrolysis

Fast pyrolysis is a high temperature process, in which biomass is rapidly heated in the absence of air, vaporizes, and then rapidly cooled to get maximum amount of bio-oil. Bio-oil which is the main product is obtained in yields of up to 80% by weight of the dry feed together with by-product char and gas which are used within the process so there are no waste streams (Bridgwater and Peacock, 2000). Figure 3.4 and Figure 3.5 shows the fast pyrolysis process and its application.

Parameter	Pyrolysis process		
	Conventional	Fast	Flash
Operating temperature (°C)	300-700	600-1000	800-1000[a]
Heating rate (°C/sec)	0.1-1	10-200	≥1000
Solid residence time (sec)	600-6000	0.5-5	<0.5
Particle size (mm)	5 - 50	<1	Dust

[a] up to 2000 °C with solar furnaces

Table 3.3 Operating parameters of different pyrolysis processes (Maschio et al. 1992)

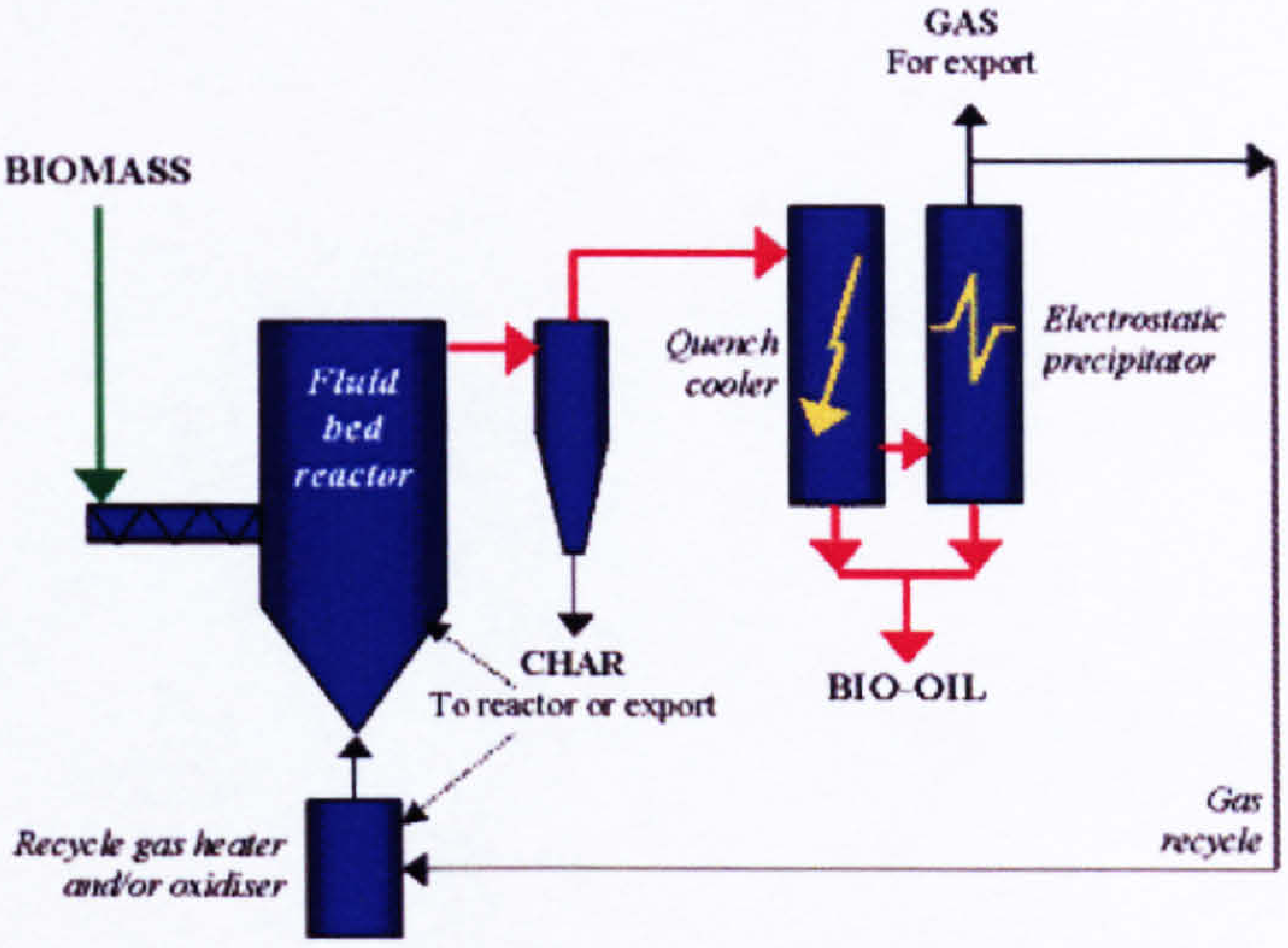


Figure 3.4 Principles of typical fast pyrolysis process (PyNe, 2005)

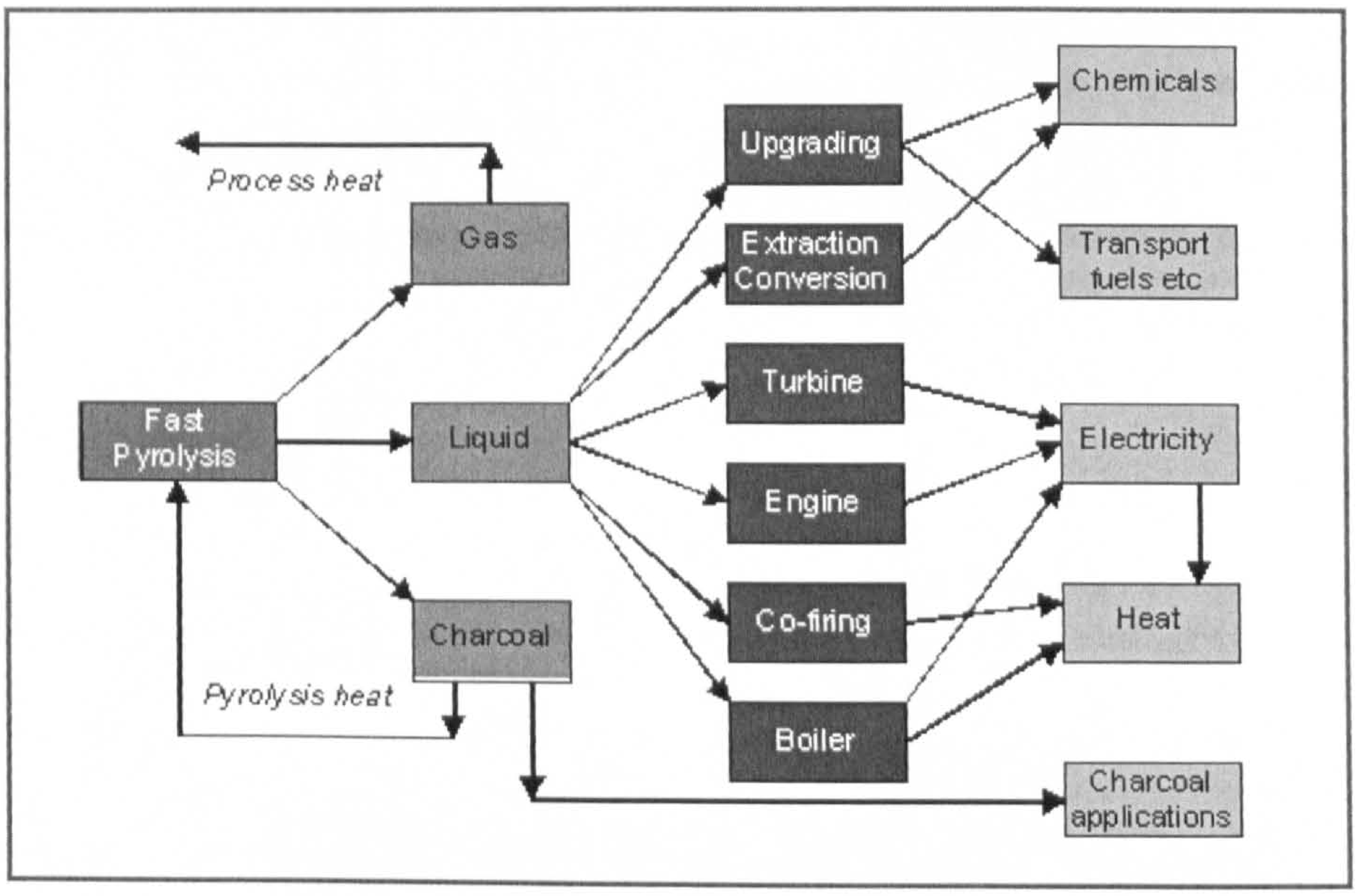


Figure 3.5 Application of fast pyrolysis product (PyNe, 2005)

The main components of a typical fluidized-bed fast pyrolysis system are (Brdgewater and Peacocke, 2000; PyNe, 2005):

- Feed drying. Unless a naturally dry material such as straw is available, drying is usually essential to prevent water being included in the bio-oil.
- Grinding. Particles have to be very small to fulfill the requirements of rapid heating and to achieve higher liquid yields.
- Reactor configuration. The essential features of a fast pyrolysis reactor are: very high heating and heat transfer rates; and rapid cooling or quenching of the pyrolysis vapors.
- Vapor residence time. The time and temperature profile between formation of pyrolysis vapors and their quenching influence the composition and quality of the liquid product. A few hundred milliseconds of vapour residence times are necessary for optimum yields. Longer residence times result in significant reductions in organic yields.
- Liquid collection. Pyrolysis liquid is mostly in the form of aerosols rather than a true vapour. Quenching, i.e. contact with cooled liquid is effective but careful design and temperature control is needed to avoid blockage from differential condensation of heavy ends. Electrostatic precipitation has been shown to be very effective in recovering the aerosols.

The elemental and chemical composition of pyrolysis oils is very much dependent on the pyrolysis conditions under which they are produced - see Figure 3.6. Typical characteristics of fast pyrolysis liquid are shown in Table 3.4. They vary considerably according to the feed material and its characteristics.

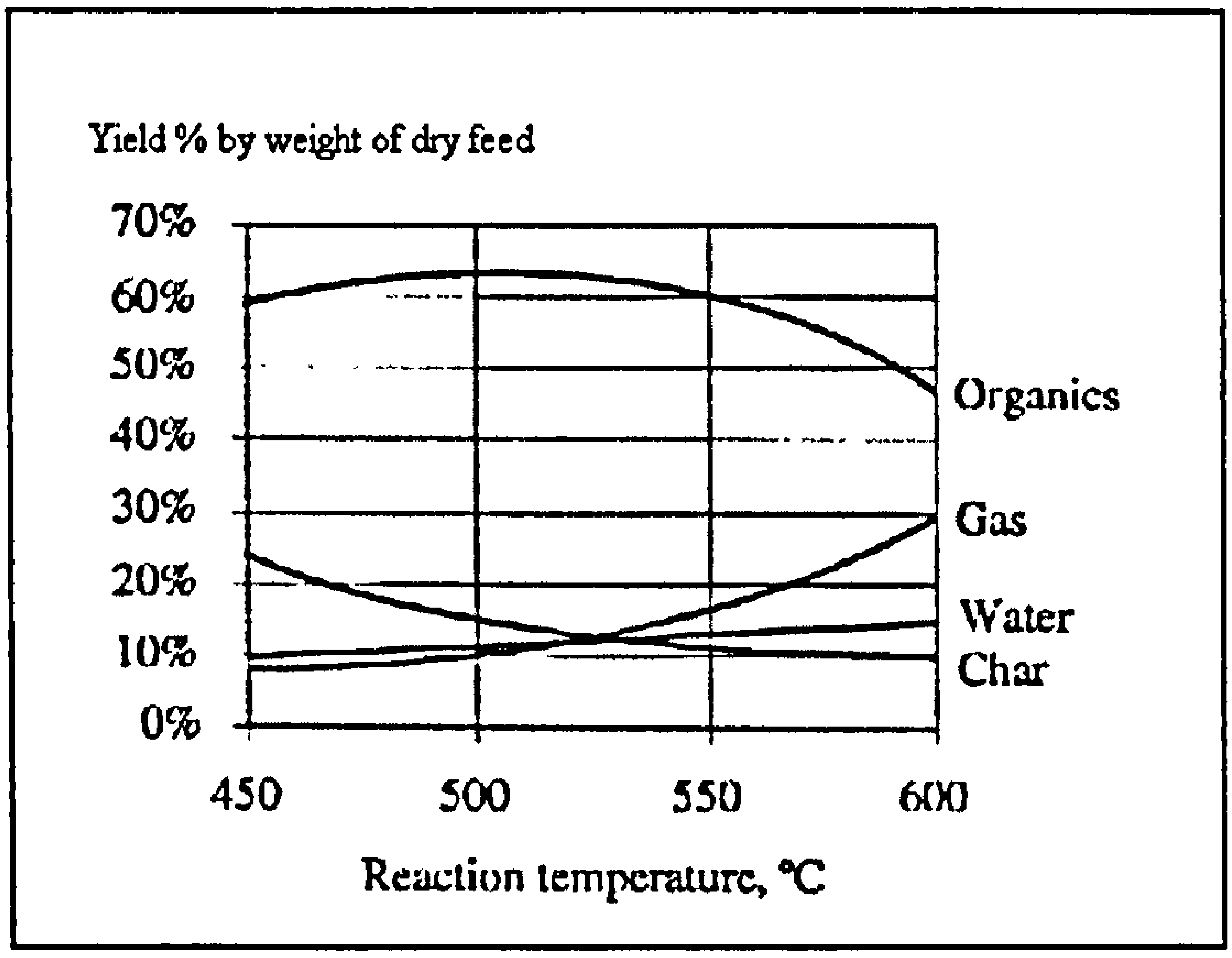


Figure 3.6 Typical yields of organic liquid, reactors water, gas and char from fast pyrolysis of wood (Bridgwater et al. 1999)

Physical property	Typical value
Moisture content	25.0 %
pH	2.5
Specific gravity	1.2
Elemental analysis (moisture free basis):	
C	56.4 %
H	6.2 %
N	0.2 %
S	<0.01%
Ash	0.1%
O	37.1%
Higher heating value (moisture free basis)	22.5 MJ/kg
Higher heating value - as produced	17.0 MJ/kg
Viscosity (at 40°C)	30-200 cp.
Pour point	-23.0°C

Table 3.4 Typical characteristics data of fast pyrolysis liquid (Bridgwater et al. 1999)

3.4.2 Electricity Generation by Pyrolysis of Biomass

Bio-oil has the advantage of being storable and transportable. Electricity can be produced from bio-oil by direct combustion, ICE and gas turbines. One of the big challenges for bio-oil is the cost, which is 10% to 100% more than fossil fuel (PyNe, 2005). Examples of the applications of pyrolysis liquid product for electricity generation:

- Combustion: Bio-oil has been successfully used as a fuel by many organizations both in pilot and commercial scale. Successful tests have been carried out at Canmet in Canada, at MIT in the USA, and by Neste in Finland, and the bio-oil is routinely used as a boiler fuel by Red Arrow in USA. Problems reported are the high viscosity, which is adjusted by addition of alcohol by Neste and by preheating by Canmet. In both cases, the boiler or furnace requires preheating with conventional fuels before switching over to bio-oil and a more complex start-up sequence is therefore required as bio-oil is not miscible with fuel oil or diesel (Bridgwater and Peacocke, 2000).

- Engines: Successful tests have been carried out to run the dual-fuel engines with crude bio-oil without any pre-treatment. The organizations that have gained experience include Motori and Pasquali in Italy, Kannas University and MIT in USA, and Wartsila in Finland. Ormrod diesels, UK have succeeded in operating a 250 kW_e medium speed, dual fuel engine (Europa, 2005; Bridgwater and Peacocke, 2000).
- Gas turbines: ENEL, Italy has studied the effect of bio-oil combustion in gas turbines in a static test rig. Long-term operational experience is required to establish optimum conditions (Bridgwater and Peacocke, 2000).

3.5 Anaerobic Digestion of Biomass

Anaerobic digestion is a process by which a mixed microbiological culture attacks a complex organic material in the absence of oxygen resulting in the generation of biogas together with solid and liquid effluents. Principal constituents of the biogas generated are CH_4 and carbon dioxide CO_2. Manures from cattle and poultry, MSW, sewage sludge are the examples of biomass resources from which biogas are produced by anaerobic digestion. Depending on the specific composition of the organic material and the nutrients available, small amounts of other gases such as hydrogen, nitrogen and hydrogen sulfide may be produced, the reaction involved can be expressed as (IWM, 1998):

$$\text{Organic Matter} \xrightarrow{\qquad\qquad} CH_4 + CO_2 + N_2 + NH_3 + H_2S$$

There are three effective temperature ranges for anaerobic digestion, each of which has its own favored group of bacteria and its own set of characteristic advantages and disadvantages. These are (IWM, 1998):

- cryophilic (<20°C)
- mesophilic (20-45°C)
- thermophilic (50-65°C)

Anaerobic digestion under cryophilic condition is not generally adopted due to low rate of reaction. IWM (1998) reported that, practical anaerobic digestion systems are operated under either in mesophilic (usually 35°C) or in thermophilic condition (usually 55°C) conditions. The optimum mesophilic or thermophilic temperature might vary with the composition of biomass and the type of digester. In any anaerobic digestion system, the reactor temperature must be maintained at a relatively constant level to maintain the biogas production rate. The higher heat input required to maintain thermophilic conditions might not be economic and greater sensitivity to operating and environmental variables makes the higher-temperature operation more problematic than mesophilic digestion (IWM, 1998).

There are three main stages to anaerobic digestion. These are hydrolysis, acidogenesis and methanogenesis - see Figure 3.7.

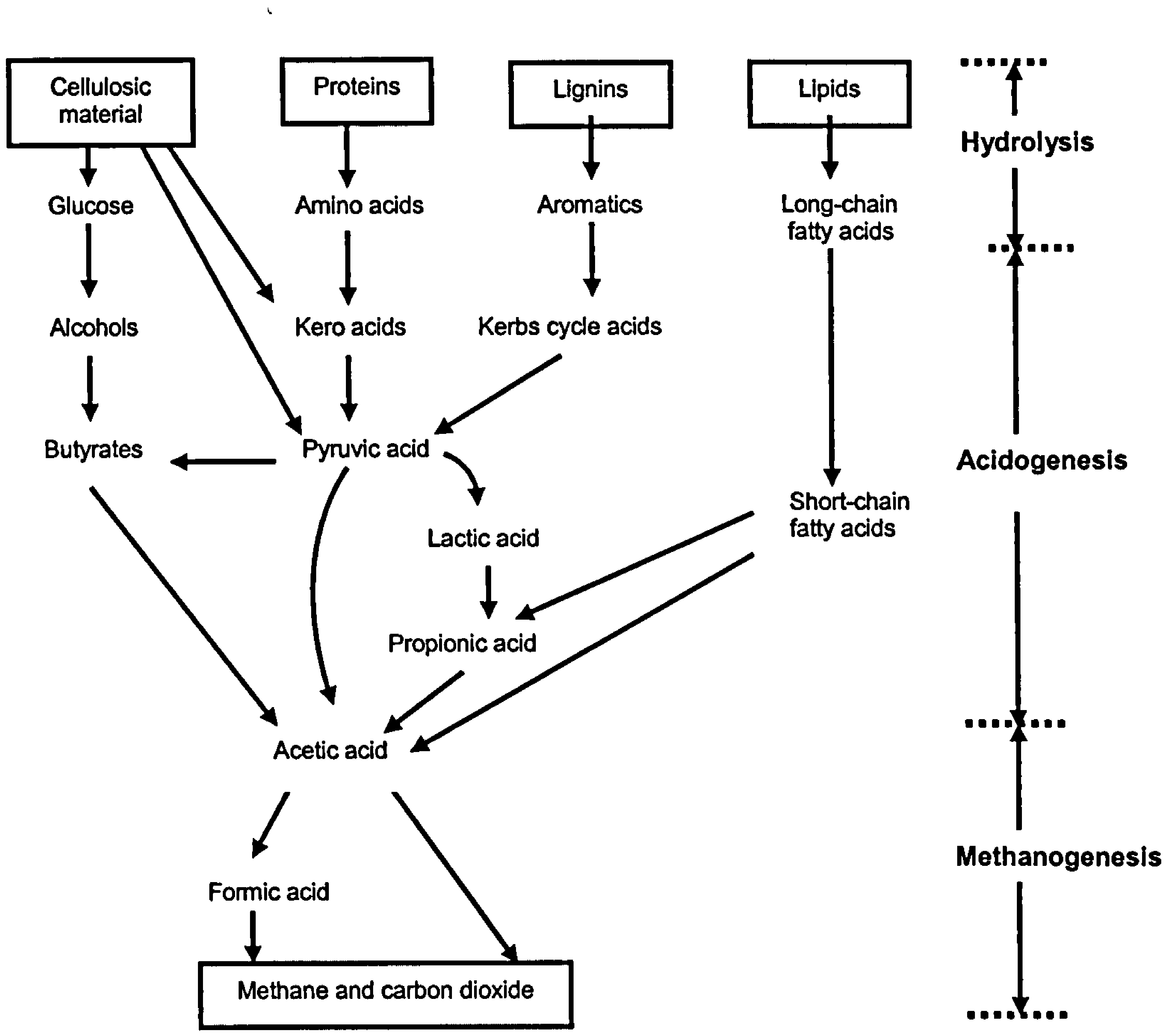


Figure 3.7 Simplified descriptions of biochemical pathways in anaerobic digestion of biomass (Sϕrensen, 2000)

Brief descriptions of each stage are as follows (IWM, 1998; Sϕrensen, 2000):

- **Hydrolysis.** This is the first stage in which complex insoluble organic polymers, such as carbohydrates, cellulose, proteins and fats are broken down and liquefied by the extra-cellular enzymes produced by hydrolytic fermented bacteria (e.g. Clostridium, Eubacterium and Peptococcus). In this stage proteins are converted into amino acids and carbohydrates into simple sugars and fats into long-chain fatty acids.

- **Acidogenesis.** This stage is characterized by the production of acetic acid, and volatile fatty acids which are derived from the protein, fat and carbohydrate components of the feed stock. pH falls as the amounts of these compounds increase. CO_2 and H_2 are also evolved as a result of the catabolism of carbohydrates, with the additional potential for the production of methanol and/or other simple alcohols.

- **Methanogenesis.** Methane is produced in this stage through the breakdown of the products of previous stage. Methane is produced from a number of simple substrates, acetic acid, methanol, carbon dioxide and hydrogen.

3.5.1 Electricity Generation by Anaerobic Digestion of Biomass

Biogas is a versatile fuel. Biogas can be used for all applications designed for natural gas. Utilization of biogas in the internal combustion engines is a long established technology. Biogas is also burnt for lighting purposes to replace the use of kerosene oil in the rural areas in developing countries. China and India have long-term experience with small-sized biogas plants.

Diesel engines can be operated in dual-fuel mode of operation (diesel plus biogas). One of the big advantages of this type is that in case of shortfall in biogas supply; the engine switches over smoothly without interruption to conventional diesel operation. The biogas is mixed with the air before the mixture enters the combustion chamber, and at the end of the compression stroke a pilot quantity of diesel is injected to ignite the mixture. NO_x emissions are usually low for biogas engines, whereas CO concentration is often more of a problem. But from the environmental point of view, CO is a far smaller problem than NO_x because it is rapidly oxidized to CO_2. Less amount of NO_x and CO is achieved with lean burn mixture (IEA Bioenergy, 2003b).

3.6 Fermentation of Biomass

Liquid fuels can also be produced from biological raw materials through anaerobic fermentation process. The liquid fuel (i.e. alcohol) is separated from other components by distillation. If the material is sugarcane, the fermentation reaction may be summarised as:

$$C_6H_{12}O_6 \longrightarrow 2\,C_2H_5OH + 2CO_2$$

3.6.1 Production of Ethanol and Methanol

3.6.1.1 Ethanol

Ethanol can be produced from the following three main types of biomass feed stock (Wereko-Brobby and Hagen, 1996):

- sugars (e.g. sugar cane, molasses);
- starches (e.g. cassava, corn); and
- cellulose (e.g. wood, agricultural residues)

Sugar-bearing feed-stock is attractive for ethanol production, as they already contain the simpler sugar forms such as glucose or fructose, which can be fermented to ethanol directly. Starches contain carbohydrates of greater molecule complexity and therefore have to be broken down to simpler sugars by another process, which will increase the capital and operating costs. Cellulose or carbohydrates have an even greater molecular complexity and have to be converted to fermentable sugars by acid or enzymatic hydrolysis (Wereko-Brobby and Hagen, 1996).

Production of ethanol involves pre-treatment of the feed stock, fermentation and ethanol distillation. If the feedstock is sugarcane, the cane is first washed, crushed and filtered to separate the bagasee. The sugar juice is further concentrated and sterilized before fermentation. For starch-containing raw materials the pre-treatment also involves hydrolysis of the starch molecules by enzymes into fermentable sugar. Once the fermentable sugar is formed, processing is identical for sugar and starch materials. Conventional ethanol technology uses batch fermentation with common strains of yeast to produce an 8-10% alcohol solution after 24-72 hours of fermentation (Wereko-Brobby and Hagen, 1996). The ethanol solution is then distilled in a multistage distillation column to a concentration of about 95%. If anhydrous alcohol is the desired product, which is the case when ethanol is used for blending with gasoline, benzene is added to a third distillation column to split the azeotrope ethanol and water forms at a 95% concentration of ethanol. The anhydrous ethanol contains 99.8% of ethanol (Wereko-Brobby and Hagen, 1996).

3.6.1.2 Methanol

High-cellulose content materials such as wood and agricultural residues are suitable for methanol production. The production technology for methanol is totally different from the ethanol production. Raw material is converted into a gaseous intermediates from which methanol can be synthesized. For economic reasons, methanol will probably be produced in large plants. The minimum economic capacity for a methanol production plant using biomass as feedstock is seldom considered to be lower than $3x10^5$ tonnes of methanol/year (Wereko-Brobby and Hagen, 1996).

3.6.2 Electricity Generation by Fermentation of Biomass

Alcohol can be used as a liquid fuel in ICE-generator, to generate electricity either on its own or blended with petroleum (Larkin et al. 2004). The HHV of ethanol is 30 MJ/kg and its octane rating is 89-100 (Sϕrensen, 2000). Properties of ethanol and methanol are fairly similar to gasoline (see Table 3.5). No adjustments to the engines are required for up to a 20% ethanol blend in gasoline (Wereko-Brobby and Hagen, 1996). On the other hand, straight ethanol has significantly different combustion properties to gasoline. So, it needs some modifications in the design of engine to use straight ethanol as fuel. Engines for straight ethanol combustion have been developed and introduced in Brazil (Wereko-Brobby and Hagen, 1996). Properties of diesel such as low octane number, high-vaporization heat, low viscosity make the alcohol unsuitable to use directly in existing diesel engines.

Property	**Fuel alcohols**		**Gasoline (for comparison)**
	Ethanol	Methanol	
Density kg/m^3	789.0	793.0	720-750
Higher heating values (GJ/tonne)	29.7	22.3	46.47
Lower heating values (GJ/tonne)	27.0	19.7	43.6 - 43.9
Lower heating values (MJ/m^3)	21.3	15.6	About 32.0
Stoichiometric air/fuel ratio (kg/kg)	9.0	6.5	14.6
Boiling temperature at 1 bar (°C)	78.5	65.0	30.225
Heat of vaporization (KJ/kg)	-	1110.0	400
Vapour pressure at 38°C	-	32.0	62-90
Octane number	106.0	112.0	91-100

Table 3.5 Properties of fuel alcohol's compared with gasoline
(Wereko-Brobby and Hagen, 1996)

Alcohol's have favorable combustion characteristics due to its high octane-rated performance. Internal combustion engines optimized for operation on alcohol fuels are 20% more energy efficient than when operated on gasoline, and an engine designed specifically to run on ethanol can be 30% more efficient (FAE, 2005). Engines designed to run on alcohol emits less oxides of nitrogen (NO_x) because the alcohols burn at lower temperatures than gasoline, and NO_x emissions drop with decreasing temperature (Wyman et al. 1993).

3.7 Fuel Cells

Fuel cells are electro-chemical devices that convert the chemical energy directly to electricity and heat. Fuel cell is like a battery: it consists of an anode and cathode separated by an ion-conducting electrolyte (see Figure 3.8). Hydrogen rich fuel gas is fed into the anode and oxygen (or air) over the cathode. Being encouraged by catalyst hydrogen dissociates into hydrogen ions and electrons.

Hydrogen ion passes through electrolyte to the cathode, and simultaneously the electrons move through an external circuit before they return to the cathode, to be reunited with the hydrogen and oxygen to form water. Fuel cell operates quietly and where hydrogen rich gas is used as a fuel it produces only water and heat as exhaust (cathode and anode effluent) (Shepherd and Shepherd, 2003; Larsen, 1993).

Fuel cells are highly efficient due to the direct conversion of energy into electricity. Their fuel to electricity efficiencies are typically above 40 - 60% (Batra and Bali, 2001). The fuel cell reaction is exothermic, so if co-generation is applied then the overall efficiencies can be up to 85 - 90% (Batra and Bali, 2001). Fuel cells are combined into groups (or 'stacks') to achieve a useful voltage and power output.

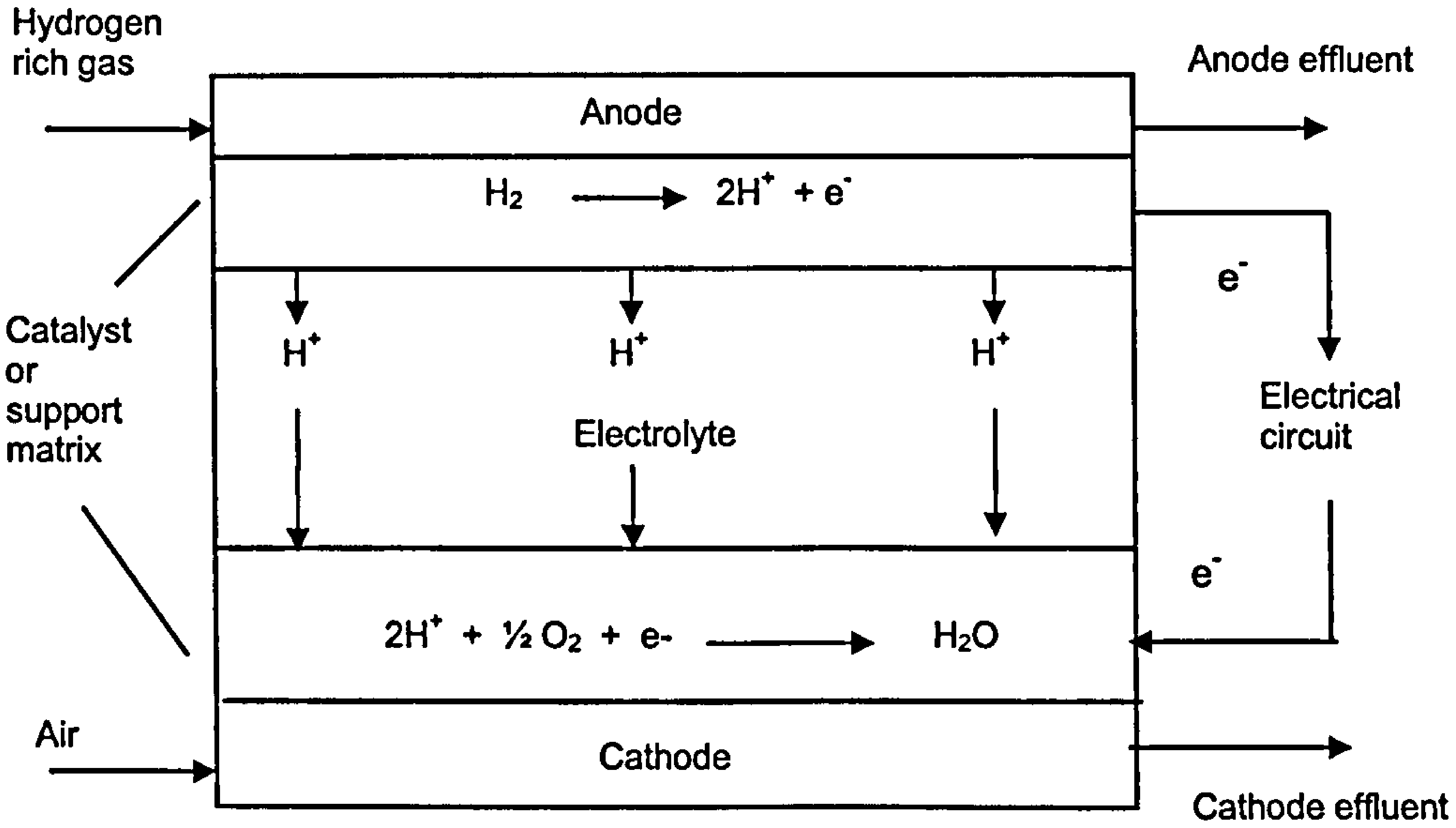


Figure 3.8 Operating principle of a fuel cell (Larsen, 1993)

3.7.1 Fuel Cell for Electricity Generation

Fuel cells are ideal for residential electricity generation, either for grid or off-grid purposes (Shepherd and Shepherd, 2003). Fuel cells are classified according to the type of electrolyte used in the cell: alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC) and polymer electrolyte fuel cell (PEFC) (Magistri, 2004). For power generation, the most promising technologies include the molten-carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC). SOFC's allow high tolerance to fuel contaminant and high temperature (IEA Bioenergy, 2003b). The operating temperatures, electrolyte and module sizes of the different types are shown in Table 3.6. Phosphoric acid fuel cells power plants in the range of 200 kW to 2 MW are operated in Japan, Switzerland and the USA. The largest unit of this type is 11 MW, operated by the Tokyo Electric Power Company (IEA Bioenergy, 2003b). MCFC's are a type of direct fuel cell which eliminates the use of external fuel processors. Fuels are converted into hydrogen- rich gas in the reforming anode which is part of the fuel cell stack (IEA Bioenergy, 2003b). The major steps followed for electricity generations from biomass-based fuel cell power plant are (Naumann and Myren, 1995):

- conversion of biomass to methane-rich gas streams or liquid fuels
- removing of impurities and converts the fuel gas to a hydrogen rich gas (i.e. fuel processor), the detailed flow sheet for this step depends on the composition of the fuel gas and the requirement of the fuel cell generator
- generation of electricity using this hydrogen rich gas in fuel cell

Table 3.7 shows some of the biogas contaminants and the issues of concerns for satisfactory fuel cell operation. Feeding the product gas of biomass gasification to a MCFC instead of a gas turbine allows one to lower the restrictions on the contaminants level, faced by the developers of the biomass power generation plants. The higher efficiency of the MCFC compared to the efficiency of the gas turbine results in higher overall efficiencies of a power plant. The estimated efficiency of the biomass gasification – MCFC is around 53%, which is considerably higher than that of combined cycle gas turbine (Labachyov and Richter, 1998).

Characteristics	Type of Fuel Cell		
	PAFC	MCFC	SOFC
Electrolyte	Phosphoric Acid	Molten Carbonate	Solid Oxide
Operating temperature (°C)	200	650	1000
System efficiency (%)	40-45	50-57	45 – 50
Module size (electrical capacity)	200 kW – 2 MW	2 MW	3 – 100 kW

Table 3.6 Characteristics of fuel cells (IEA Bioenergy, 2003b)

Anaerobic-digester gas contaminant	Fuel cell power plant requirements[a]	Issues/concern
Sulfur (H_2S)	< 4.0 ppmv [b]	Poison to fuel processor reforming catalyst
Halogens (F, CL, Br)	< 4.0 ppmv [c]	Corrosion of fuel processor components
NH_3	< 1.0 ppmv	Fuel cell stack performance
H_2O	Remove moisture and condensate	Damage to fuel control valves. Transport of bacterial phosphates
Bacteria/solids	Remove all bacteria / solids	Fouling of fuel processor piping/beds

[a] Operating on biogas (60% CH_4 and 40% CO_2), [b] With zinc oxide sulfur guard bed, [c] With optimal halogen guard bed in fuel processor.

Table 3.7 Anaerobic digester fuel contaminant limits for fuel cell applications (Spiegel and Preston, 2000)

3.8 Conclusions

There are mainly two types of biomass conversion techniques: thermo-chemical and bio-chemical conversion. Examples of the thermo-chemical conversion techniques are direct firing, co-firing (with coal or natural gas), gasification and pyrolysis. Anaerobic digestion and fermentation are the examples of the bio-chemical conversion techniques. Fuel cell converts the chemical energy directly and efficiently to electricity.

Biomass-to-electricity generation technologies are available in a variety of plant sizes, either for grid or small-to-medium scale decentralised applications. Direct combustion, co-firing, gasification and anaerobic digestion based biomass-to-electricity generation technologies are being used widely in many countries of the world.

Steam turbines and steam engines are used as proven technology to generate electricity through biomass combustion. Steam engines are available in the power range from approximately 50 kW_e to 1 MW_e and steam turbines are available in the range of 0.5 MW_e up to 500 MW_e. Co-firing of biomass with coal is well established technology. Typical capacities of these types of plants range from 5 to 20 MW_e at existing coal fired stations (Faaij, 2006).

Gasification and anaerobic digestion technologies are popular in many developing and developed countries. These technologies are used for decentralised off-grid biomass electricity generation in the developing countries. Gasification based combined cycle power plants represent a very promising prospect due to the higher efficiency that can be achieved. The technology has been demonstrated in the 5 – 10 MW_e range (Faaij, 2006).

CHAPTER 4
BIOMASS ENERGY SYSTEMS MODELLING: A REVIEW

4.1 Introduction

Many countries in the world do not have organised system to collect and analyse data for formulating biomass energy plans, policies, or strategies. Biomass energy planning is defined as to arrive at a set of agreed feasible and consistent targets for making policy for utilisation of biomass resources- mainly at national or decentralised level. Decentralized-area-based approach to planning is essential to properly understand biomass energy situation and to formulate proper site-specific plans (Heruela, 1998). Biomass energy planning which aim at the efficient, economical and sustainable supply and utilisation of biomass energy can be viable for many countries. A general framework of biomass energy planning technique is shown in Figure 4.1. The biomass energy planning is a continuous and iterative process (see Figure 4.1). Close interactions are important to review the results of different steps in the planning process, which lead to new analyses and projections. Models are used as tools, to assist planners to perform different analyses. Models simplify the reality for the sake of analysis. It is defined, or normally implicitly understood, as an algorithm for the prediction of the performance of a system as a function of a number of control parameters. The standard sequence of activities in modelling are: problem awareness, formulation of the problem, modelling, validation, problem solving, analysis of the results, presentation of the results, and implementation (Roos and Rakos, 2000).

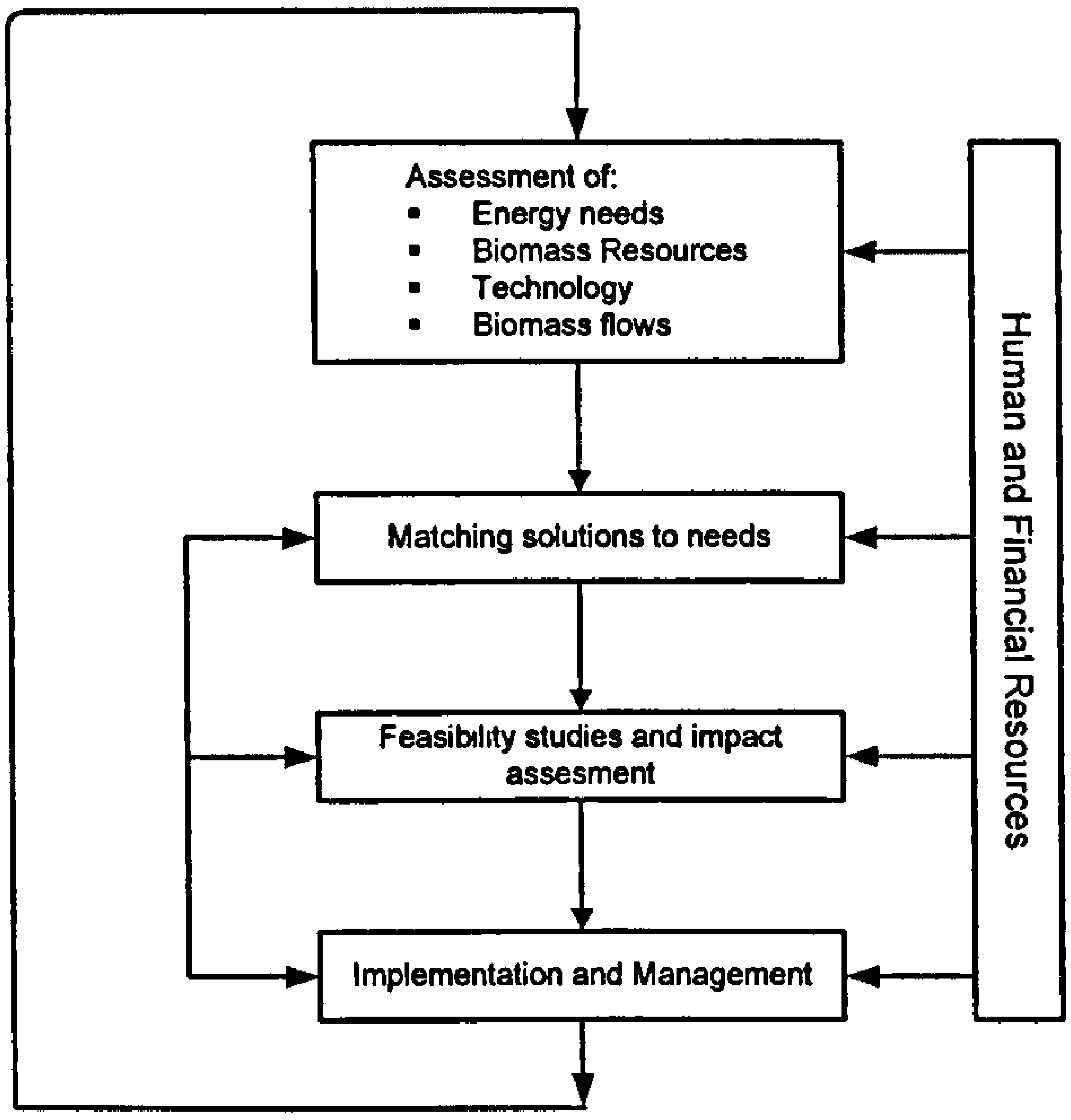


Figure 4.1 Framework for biomass energy planning (RWEDP, 2000)

In modelling biomass energy systems, three features have to be considered (Roos and Rakos, 2000):

- Biomass fuel sources and conversion techniques are more often than fossil-fuel systems dependent on local conditions concerning biomass feedstock supply and energy use, which restricts the applicability of a model that have been developed under one set of conditions to other situations.
- There are few developed and documented full-scale biomass-energy systems in operation. Due to transport costs and low market penetration, few global markets for biomass fuels exist.
- Biomass fuels are frequently the by-products of some major activities e.g. forestry, agriculture and waste management.

4.2 Energy Systems Modelling

Different types of energy models exits, depending on the approach and objectives. Demand and supply analyses, economics, conversion technologies and optimisation these are the major issues analysed in different types of the modelling techniques.

Roos and Rakos (2000) reported that there are two basic energy modelling techniques: Process Models and Econometric Models. RWEDP (2000) reported the types of energy modelling techniques are as Econometric and Techno-economic. Process models make explicit assumptions about costs, performances and relations between components in the energy system and calculate feasible energy strategies either by optimisation (e.g. minimisation of system costs) or by simulation of alternative scenarios.

Econometric models use historical data for statistical analysis and extrapolations of possible developments in the future. These are mainly demand models and are based on the assumptions that energy demand is driven by macro-economic indicators such as GDP, income, fuel prices (RWEDP, 2000). Future demand is forecasted by employing statistical data to establish relationships that describe the energy demand as a function of a number of macro-economic variables, mainly income and prices.

On the other hand, a techno-economic model analyse the energy-end uses (i.e. cooking, heating, lighting) and calculates the economics for each-end use, on the basis of technical, economic and social indicators (RWEDP, 2000). In this type of modelling technique, different scenarios are developed and analysed (simulation approach) to assess the impact of different factors which are related to energy or economic policy.

Optimisation model is considered as another separate broadest category of energy modelling technique (Heaps, 2002; Suganthi and Williams, 2000). Heaps (2002) described another type of modelling technique - accounting framework. Figure 4.2 explains the accounting framework and optimisation modelling techniques.

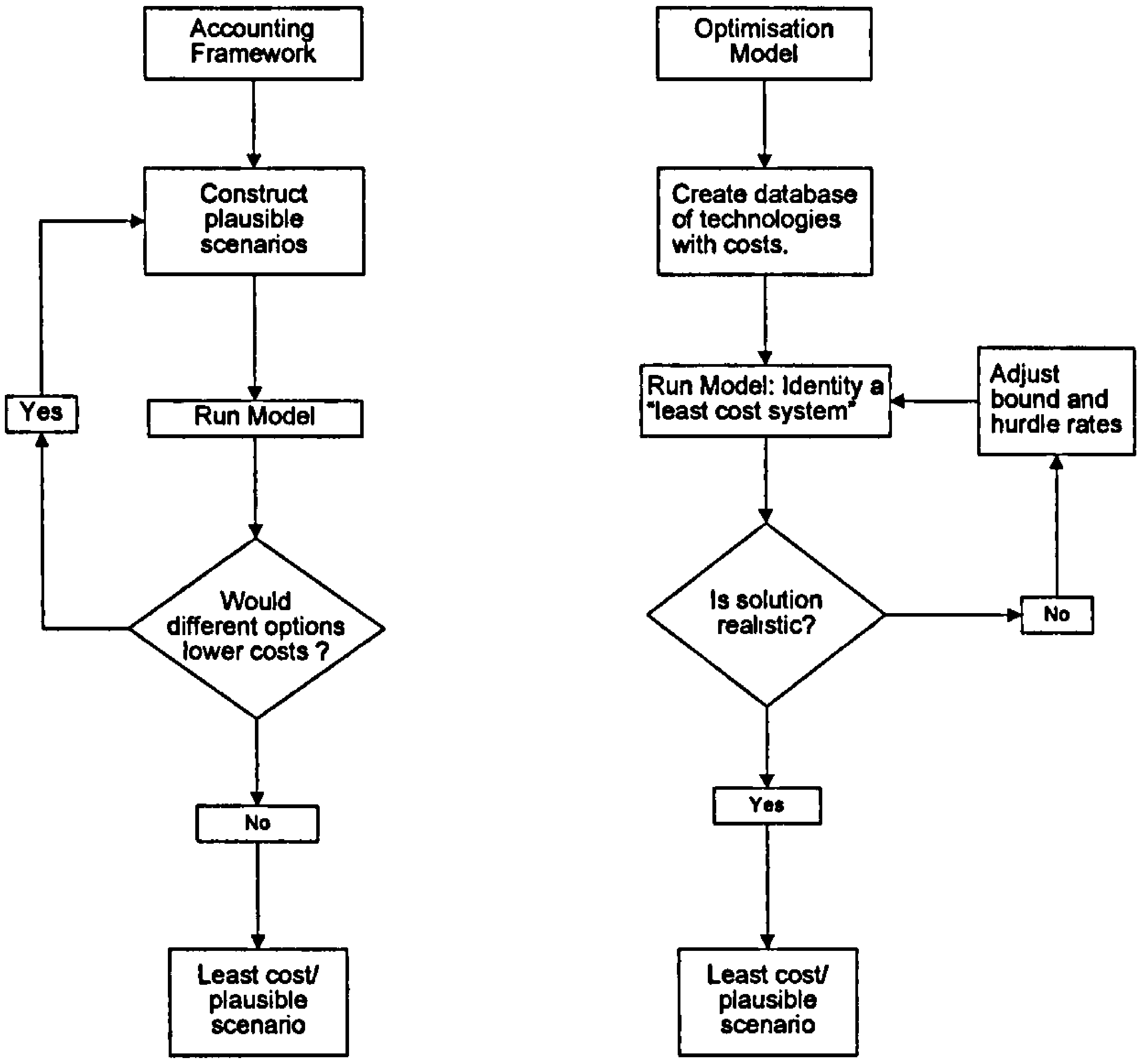


Figure 4.2 Accounting frameworks and optimisation models in practice (Heaps, 2002)

In accounting frameworks, it explores the resource, environment and social cost implications of alternative future "what if" energy scenarios. In this type, the modeller explicitly accounts for outcomes of a decision. It has the advantages of simplicity, flexibility, lower data requirements and the capability of examining issues that go beyond technology choice. On the other hand, this type of modelling technique is less suitable where systems are complex and a least cost solution is needed. Accounting framework type of modelling technique has the similarity with the econometric (or techno-econometric) types of modelling techniques.

Geographical Information Systems (GIS) is another type of energy modelling technique. GIS are defined as a combination of computerized-cartography system (that stores map data) and a database management system. It is a powerful tool for collecting, sorting, retrieving, transforming and displaying spatial data. All possible geographical entitles can be modelled within a GIS environment as point, line, or polygon objects. Attributes are stored in the form of database fields and are referenced to the corresponding geographical objects. Each geographic object and its attributes represent a database record. A set of records referring to objects with the same attributes represents a table, which can be presented either as a map (geographic objects) or a browser (data field). GIS environments are not just extensions of the capabilities of conventional database systems, but a dynamic environment able to accommodate and handle complicate geographic data structures and provide comprehensive information (Voivontas et al. 2001; Rodriguez-Bachiller, 1995).

4.2.1 Biomass Energy Systems Modelling

Based on the review presented in section 4.2, biomass energy systems modelling practises have been categorised mainly as: econometric (or techno-econometric) models, optimisation model, GIS models and hybrid models (combination of more than one type of modelling techniques).

4.2.1.1 Econometric Models

Junginer (2000) developed a methodology for setting up fuel supply strategies for large-scale (between 10 and 40 MW_e) biomass-energy projects using agricultural and forestry residues, which explicitly takes risks and uncertainties regarding availability and costs in relation to time into account. The methodology has been demonstrated as a case study in the north-eastern part of Thailand. Biomass price and availability have been analysed under different risk scenarios. It was concluded that assessing the risks of biomass fuel supply is vital for biomass electricity plants. In this modelling methodology, the other issues (e.g. technology choice, plant economics, social and environmental impact) of the biomass electricity plant were not analysed.

Mitchel (2000) has developed an econometric model for biomass energy application, based on a decision support system (DSS), with special reference to harvesting wood for energy from conventional and short-rotation forests. This model estimates delivery costs for wood fuel from forests in the UK.

An integrated technical and economic model (i.e. techno-econometric) was developed for biomass electricity generation at village level and applied to the Indian village of Malgudi in the Karnataka State (Bharadwaj et al. 2000). The biomass resources considered were rice straw and husk, sugarcane leaves and straw, sugarcane bagasse and coconut shells.

The International Energy Agency developed the Bioenergy Assessment Model (BEAM) in 1992, with the purpose to build a computer based model to compare various biomass production processes and conversion systems. BEAM is an econometric type modelling technique; where cost and technical performance analyses of integrated biomass energy systems can be performed in excel modules. Users can input/change the default values of some parameters, like exchange rate, project life, annual interest rate, inflation rate, and maintenance cost, overhead cost and labour cost. The outputs of the model are: technical and economic indices of different bio-energy systems; which include: unit production cost, technical performance, and financial parameters NPV including Payback period (Madlener and Myles, 2000). The model is particularly useful for developers designing biomass energy system and whilst it does indicate profit and expenditure, it does not specify a project's impact upon the local economy or environment. It is used to model a number of biomass electricity projects both in Europe and USA (Madlener and Myles, 2000).

Biomass Socio-Economic Multiplier (BIOSEM) is a software tool developed under the European Commission's Fifth Framework Programme. The objective was to construct a quantitative economic model to capture the income and employment effects arising from the deployment of biomass energy plants in rural communities. The model can be used to assess the merits of different policy packages on biomass energy production. This modelling technique is applicable for regional and local biomass energy project evaluation (Madlener and Myles, 2000).

Another computer programme BIOSIMS was developed by Parikka (2000) to calculate the amount of biomass available to use as a fuel. The model was developed using the Statistical Analysis System (SAS) software package. The model can be used for energy planning. The developed model was used for a case study for a region in Sweden. It was concluded that the model can be used for other countries (Parikka, 2000). The model does not address the technical and economical issues related to the biomass electricity systems.

The Long-range Energy Alternative Planning (LEAP) is an integrated energy-environment and greenhouse gas mitigation analysis model-building tool, developed by the Stockholm Environment Institute, Boston (Heaps, 2001). This software can create econometric models by analysing biomass consumption, conversion and resource availability in a given area or region. By using demand analysis tools and transformation tools, it is possible to simulate alternatives. Transformation analysis can be used to study inter-regional transportation of biomass fuels. LEAP contains an environmental database, which contains the data on emissions of materials to the atmosphere, water and soil for typical end-use and transformation devices, such as cook stoves, boilers and charcoal kilns (Heaps, 2001). The main disadvantage is that different types of biomass electricity technology options and related economic analyses are not included in the software. LEAP has been used for biomass energy analysis in Nepal (WECS, 2001) and in the Phrao district of Northern Thailand (Siteur, 1997).

Costs, environmental impacts and macro economic impacts of energy (crop, electricity generation) systems were assessed and compared in two industrialised countries, Ireland and the Netherlands, and one developing country, Nicaragua (Broek et al. 2002). The results were compared with electricity production based on fossil fuels. Techno-econometric modelling technique was used in this study. The study also looked at the possibility of biomass energy related trade between the countries considered. It was concluded that the country context can have large impacts on the performance of systems that produce electricity utilising energy crops. The study did not consider the utilisation of agricultural or forestry residues and only direct combustion or co-firing of biomass fuel was used as the conversion technology.

4.2.1.2 Optimisation Models

Different mathematical models were developed by researchers for the optimisation of single or multiple-variable biomass electricity plants (Kanniappan and Ramchandran, 1998; Kanniappan and Ramchandran, 2000; Krukanont and Prasertsan, 2003; Kumar et al. 2003; Krukanont and Prasertsan, 2004). A linear programming model was developed by Kanniappan and Ramchandran, (1998) to optimize the distribution of land for different crops in order to maximise the surplus biomass production. The model has two groups of linear constraints. The first group of constraints was designed for the minimum production requirements of cereals, pulses, oilseeds, sugar, vegetables, and residues as fuel and animal feed to provide the requirements of the area. The second group was built for the available resources such as land area, human labour, animal power, and tractor power. The developed linear-programming model was linked to the Hyper Lindo software package to achieve the optimal solution required. Three different scenarios were used:

- availability of biomass according to the existing cropping pattern
- biomass that can be generated through the model solution
- biomass that can be generated through the model by way of increasing the total irrigated area in the two agricultural seasons of the year by 10%

Kanniappan and Ramchandran (2000) developed multiple objectives optimisation model in order to make an area self sufficient in energy. The objectives functions used in the study are electricity consumption, commercial energy consumption, generation of electricity from biomass and food production of that area. The constraints are human power, animal power, tractor power, land area and energy requirement of the area (such as cooking energy, lighting energy and energy for other operations). The developed model was applied for a typical area in the Didigul district of Tamil-Nadu State in India.

Mathematical relationship of the biomass fuel cost as a function of various economical parameters was developed for direct combustion based co-generation plant (Krukanont and Prasertsan, 2003). It was concluded that the maximum affordable fuel cost is dependent on the fuel moisture content, area-based annual availability of biomass, the required financial return, size of the power plant, and the operation of the power plant. Optimal capacity of the biomass electricity plant was calculated for maximum affordable fuel cost, for a given location of known area based biomass availability density (Krukanont and Prasertsan, 2004). The model was used in a case study in the southern part of Thailand. GIS data of rubber growing was used to locate the appropriate sites and sizes of the rubber wood residue-fired power plants.

Optimal plant sizes were calculated on the basis of the minimum electricity generation cost using agricultural residues (grain straw), whole boreal forest and forest harvest residues in western Canada (Kumar et al. 2003). Only the direct combustion of biomass was considered in this study for modelling. Similar to the finding of Krukanont and Prasertsan (2004), the study revealed that the optimal size of power plant increases with increasing biomass yield per unit area.

HOMER is an optimisation model software, for off-grid or small grid-connected distributed power supply system. It was developed by NREL, US Department of Energy. It determines the optimal architecture and control strategy of the electricity generation system based on the least cost system configuration (NREL, 2005). HOMER also performs sensitivity and environmental impact analyses. The software can be used to identify the cost-minimising combination of different power generating technologies (pure biomass and dual-fuelled with different combinations) – to suit the load profiles. The inputs for HOMER are the electricity demand load data, biomass availability data, basic cost and performance data for each component, fuel price and interest rate. Analyses of the biomass availability, consumption are not addressed by HOMER. Moreover, the selection of biomass to electricity conversion technology is limited to types.

4.2.1.3 GIS Models

For a GIS model, input data sources can be from existing maps, field observations, aerial photographs, satellite imagery, tables and reports. Applications of GIS models for biomass energy planning are to evaluate the biomass resources, biomass electricity plant site selection and to assess the accessibility of the forest resources for fuel wood collection. The low-cost GIS tool provides accurate, consistent and robust estimates that are easy to update on a periodical basis (Haider, 2001). The GIS technique has been used in a case study for decentralised biomass energy planning at the Phrao district in Northern Thailand (Siteur, 1995).

A computer based decision support system, BRAVO (Biomass Resource Assessment Version One) was used in estimating the costs of supplying the wood fuel to any of the

12 coal-fired power plants in USA for the Tennessee valley authority (Noon and Daly, 1996). BRAVO was developed in a GIS platform, which is capable for an efficient analysis of the transportation network, thus enabling accurate estimates of hauling distances and related costs. BRAVO modelling system was effective in determining the cost and supply of potential biomass fuels for co-firing within the study region. The study concluded that BRAVO could be used in other regions as well if the input GIS data are available.

Voivontus et al. (2001) proposed a GIS-based decision support system to estimate the potential for electricity production from agricultural residues in the island of CRETE in Greece. The model handles all possible restrictions and candidate power plants are identified using an iterative procedure that locates biomass energy units and determines the cultivated area that is needed for biomass collection. It was concluded that the main parameters that affect the locations and number of biomass energy conversion facilities are plant capacity and spatial distribution of the available biomass resources.

4.2.1.4 Hybrid Models

Fiala et al. (1997) developed a mathematical model to determine the optimal electricity-generation plant capacity. Optimal plant size was calculated to achieve a NPV of zero. Based on the optimal plant size, technical and economical studies were performed for the whole of Italy considering only a specific type of conversion technology - direct combustion co-generation. Optimisation and econometric modelling techniques were both are used in this study.

Biomass-based economic energy supply structure was modelled by employing mixed-integer linear optimisation technique, integrated with a decision support system (Nagel, 2000a). Economic potential, type of feasible technology, plant economics, CO_2 emissions and biomass fuel supply risks are addressed in the model. The developed model was tested in the state of Brandenburg, Germany (Nagel, 2000b). It outlined the possibilities and boundaries for the use of biomass in Brandenburg. The conclusions of these two studies were:

- attempt should be made to reduce the biomass fuel price; and
- some economic measures such as CO_2 taxes, state subsidies for biomass energy plants should be adopted.

A computer program was developed by Papadopoulos and Katsigiannis (2002) for the estimation of the monthly optimal composition of mixed solid biomass fuel by minimising a cost function. Technical and economic feasibility studies of the direct combustion based co-generation plant have been integrated in the program. The model was tested for a wide geographical area in the north-east part of Eastern Macedonia - Thrace region of Greece.

Freppaz et al. (2003) proposed a decision support system to assist the biomass management for energy supply at a regional level, by integrating the GIS, optimisation and econometric modelling techniques. The developed model was applied to a small mountain area in Italy as a case study, with particular attention to the available biomass, optimal size of plant, technological aspects and economic viability (i.e. cost of energy production).

4.3 Biomass Energy Systems Modelling in Bangladesh

The first effort to model the Bangladesh energy system has began in 1981 at the Planning Commission of the Government of Bangladesh (Bala, 1997). The result of that effort was an integrated model of the Bangladesh energy supply and demand - Rural Energy and Agricultural Development Analysis (RADA) - which has been used in projections for energy policy analysis.

Biomass generation and consumption in a Bangladeshi village were estimated and a sustainable rural energy planning model using the biogas plant was developed - see Figure 4.3. This study was concentrated only for one village (Biswas, 1995) and biomass electricity generation technology option is not included in it. Econometric type modelling technique was used in this study.

Bala (1997) presented a typical example of a demand-branch structure for Bangladesh employing LEAP. In this modeling approach, the bottom-up rural energy supply and demand structure analyses has been used for sustainable rural energy planning in Bangladesh. The CO_2 emissions of the rural energy systems were estimated using environmental database of LEAP. However, biomass electricity technology options and associated economics were not been considered.

Biomass energy production and consumption were studied in 21 clusters of the households (Biswas and Lucas, 1997b). In this study, econometric type of modelling technique was used to study the economic viability of the biogas technology at a village in Bangladesh. It was concluded that the creation of the market for local biogas would make the biogas generation project feasible (Biswas and Lucas, 1997b).

Analysis of the biomass energy supply and consumption in two villages was performed by Bari et al. (1998), using questionnaire survey methods. Different types of survey methods such as broad questionnaire survey, sample questionnaire survey and physical monitoring were used to determine the most effective method. The study showed that the broad questionnaire survey gives a fairly general picture of both biomass supply and use. Biomass utilisation for electricity generation and technology option were not addressed in this model. The main conclusion of this study was biomass fuel use vary with variations in different socio-economic groups and village.

The dynamic nature of the rural energy sector in Bangladesh has been described only to a limited extent. Alam et al. (1999) presented a quantitative dynamic model for rural household biomass consumption in Bangladesh. The model was used for simulation in both the basic and policy planning modes for the period 1981-2000. A comparison between the model results and the reported values were in good agreement with an error of less than 15%. An econometric modelling technique has been used in this study.

Biswas et al. (2001) developed an integrated, ecological, economic and social model for sustainable rural development in villages in Bangladesh. The model is capable to show how a local business or cooperative approach to renewable energy technology could help create income-generating activities for rural landless and marginal farmers and women from these households. To illustrate this, a hypothetical case study including the installation of a biogas plant was carried out (see Figure 4.4). This model is an example of hybrid type modelling, which involve econometric and optimisation modelling techniques.

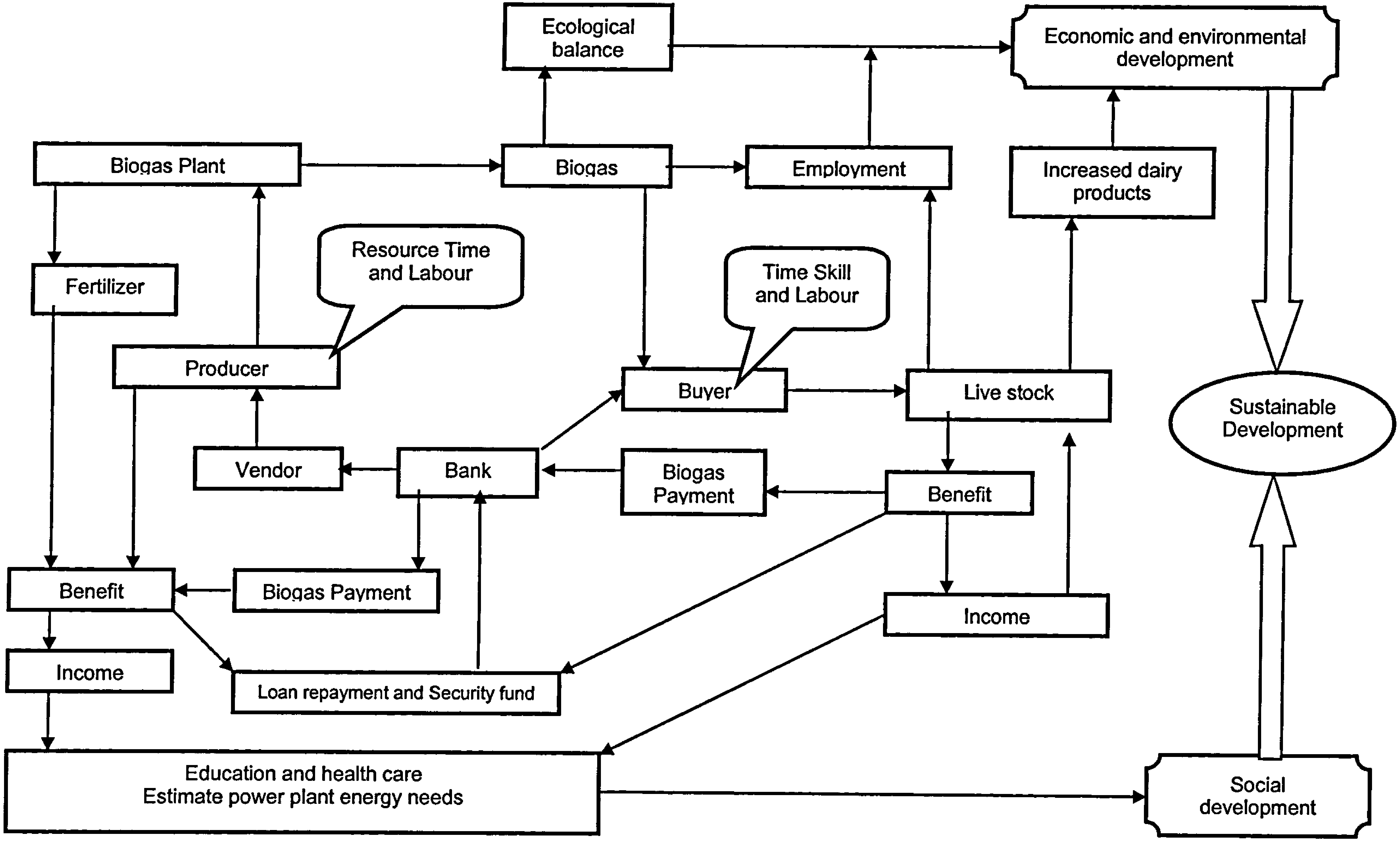


Figure 4.3 Model for sustainable rural planning using biogas plant (Biswas, 1995)

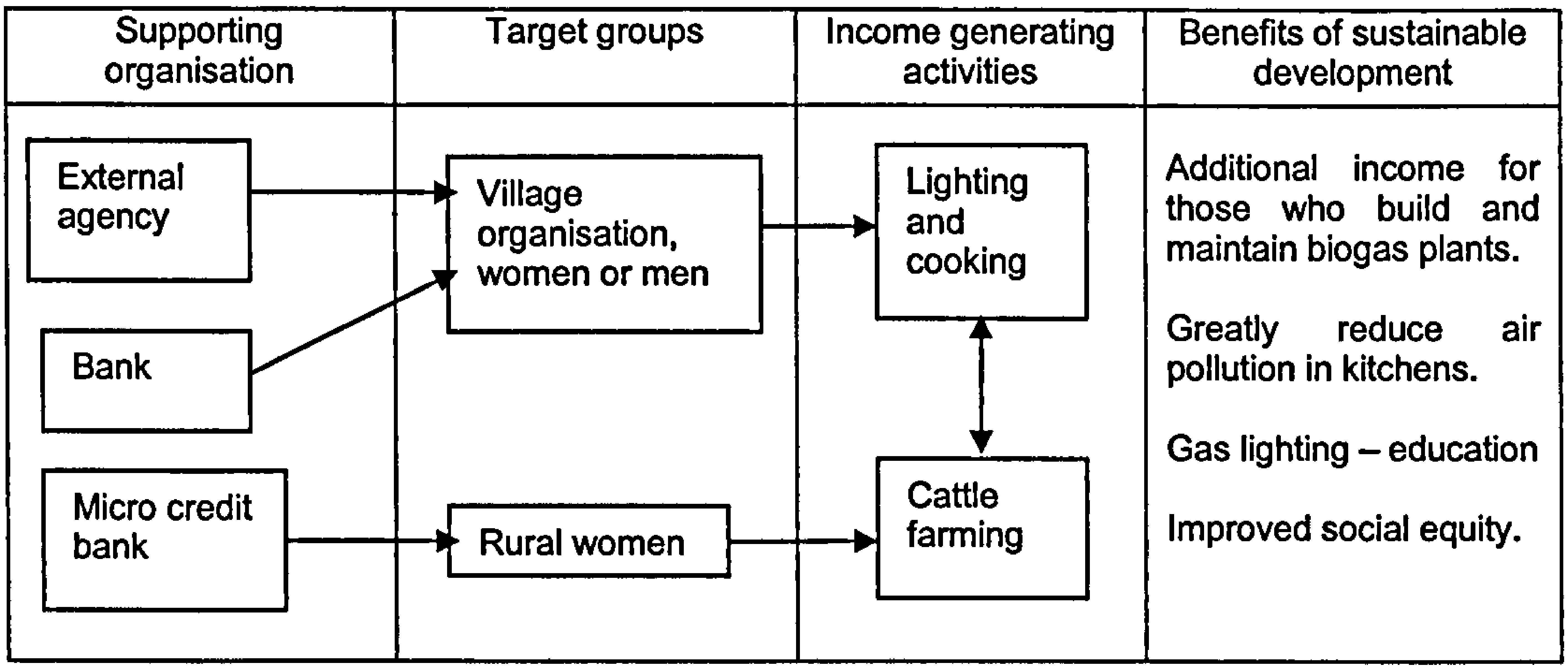


Figure 4.4 Simplified system using biogas as a cost study (Biswas et al. 2001)

4.4 Conclusions

The term 'sustainability' represents a state, and 'sustainable development' indicates a change. Sustainability is generally defined as meeting the needs of present generation without compromising the ability of future generations to meet their own needs. SERC (2005) described the term sustainability as the "fundamental principle of any energy policy: the long term maintenance of diverse and productive ecosystems upon which all life depends". For the development of third world countries, the term sustainable development does not merely refer to the change of an unsustainable economy into a sustainable one. For them, it reaches beyond that by including the pursuit of economic equity and growth (Siemons, 2002). Kartha and Larson (2000) outlined the factors related to biomass energy systems and sustainable development - see Figure 4.5).

Biomass energy situations and problems are site-specific. They vary from country to country, from province to province within countries. There is no universal tool to model biomass energy systems. Most researchers developed their own models, which are applicable to a specific country or a region. The choice of the biomass energy system modelling technique largely depends on the objectives and scope of planning. The model should match the level of planning, e.g. macro-level planning or decentralised planning.

No well established biomass energy system modelling was found for Bangladesh. For developing a sustainable biomass electricity model for Bangladesh, different issues such as biomass generation, availability, technology, costs and environmental effects need to be integrated. GIS based information is yet to be established in Bangladesh. Biomass availability, technology choice, economics and environmental effect of biomass to electricity systems could be performed by econometric modelling technique together with the help of decision support system. Optimisation technique is needed to determine the economic size of the biomass electricity plant. So, a hybrid type biomass energy modelling techniques, which is a combination of techno-econometric and optimisation techniques would be applicable for Bangladesh. Development of the computer programme is required to integrate these for building decentralised sustainable biomass electricity modelling for Bangladesh.

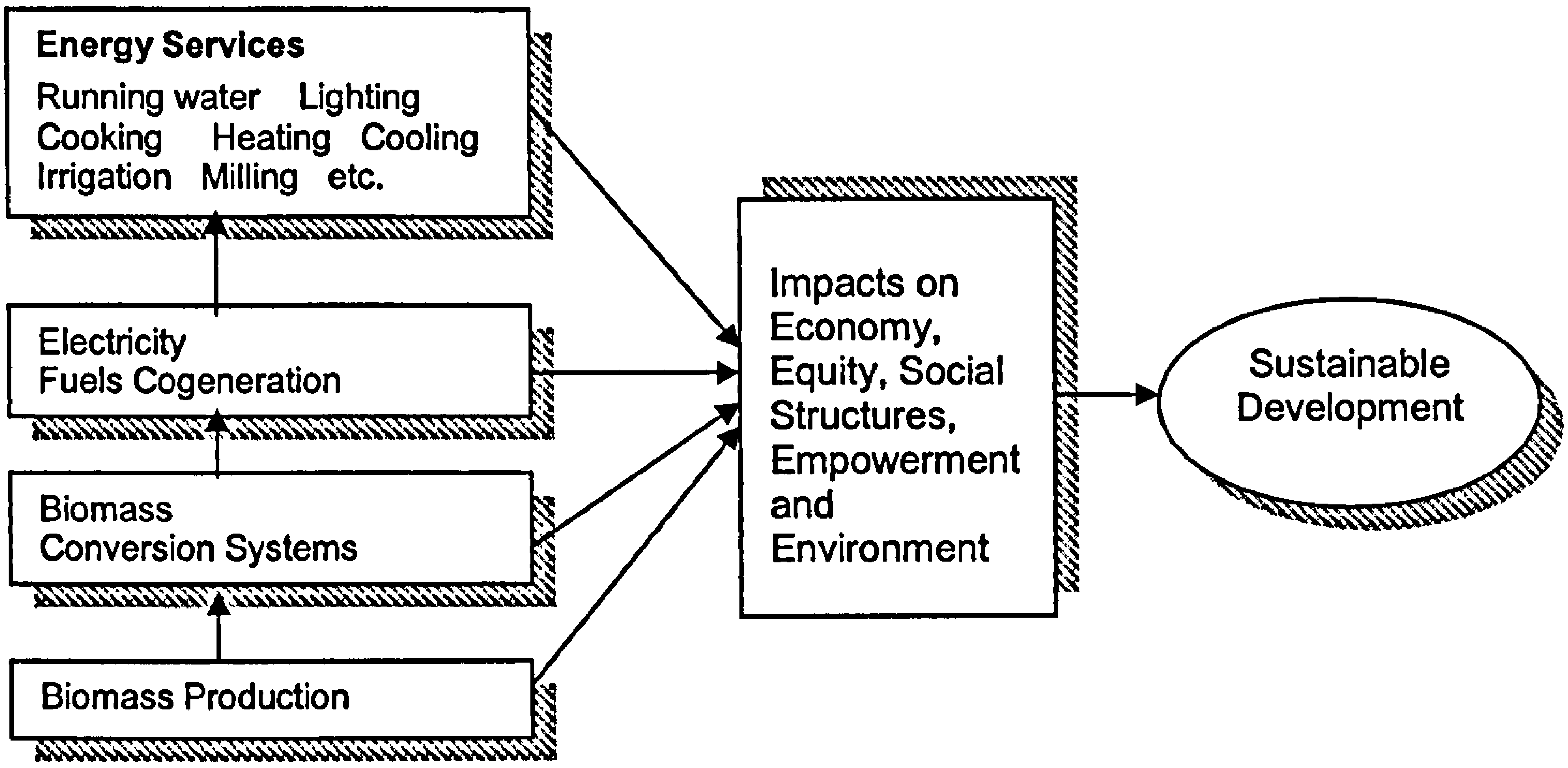


Figure 4.5 Conceptual representation of biomass energy systems and linkages to sustainable human development (Kartha and Larson, 2000)

CHAPTER 5

BIOMASS GENERATION, CONSUMPTION, AND POTENTIAL FOR ENERGY IN BANGLADESH

5.1 Introduction

Biomass energy is an important source of energy in most Asian countries. Substantial amounts of fuel wood, charcoal and other biomass energy such as agricultural residues, dung and leaves are used by households and industries. The main household applications are cooking and heating, whereas industrial applications range from mineral processing (e.g. bricks, lime, tiles and ceramics manufacturing), food and agro-processing, metal processing, textiles to miscellaneous applications such as road tarring and tire retreading. Besides these heating applications, biomass fuels (e.g. bagasse and oil palm residues) are widely used for electricity generation or the co-production of electricity and steam in industry (Koopmans and Koppejan, 1997).

The energy potential of biomass resources has been assessed in some Asian countries (e.g. in China, India, Srilanka, Thailand, and Malaysia) (Battacharya et al. 2003; Runqing and Junfeng, 2003; Yokoyama et al. 2000; and Perera et al. 2003). No such an assessment has been carried out for Bangladesh. The principal biomass resources in the country are agricultural wastes, animal waste, fuel wood, municipal solid waste and sewage sludge. In this chapter, country's total amount of available biomass resources, in 2003, has been estimated. To calculate the biomass generation rates; factors such as yield to residue ratio, moisture content and calorific value have been assumed to be the same as those employed or measured in neighboring Asian countries. Not all biomass residues generated can be utilized for energy. In some instances, it would not be economical to do so, such as when their wide dispersal or low bulk density makes recovery, transport, and storage too costly. Residues may be more valuable if used for purposes other than energy. One such use would be recycling residues onto the land, to help restore nutrients or reduce erosion. Residues might also be recovered for other domestic, industrial, or agricultural uses, such as for building materials, paper manufacturing, or animal fodder (Hall et al. 1993). Amount of biomass available for electricity generation was then estimated by deducting the biomass consumption from the amount of biomass which is recoverable. Amount recoverable is either less or equal to amount generated.

5.2 Land Use

The total land area of Bangladesh is 1.3017 x 10^{11} m^2, of which 61.6% is arable land (see Table 5.1). Bangladesh has a relatively low proportion of forest cover. In 2000, forests and woodlands represented only 10.2% of the total land area of the country compared with averages of 17.76 and 29.4% for Asia and the world, respectively (FAO Forestry, 2003). Most of the forest areas are located in the northern and eastern border parts of the country, as well as along the coast of the Bay of Bengal in the south (FAO Forestry, 2003).

Forests in Bangladesh are subject to heavy pressures in terms of both demands on wood production and competing land uses due to the large, increasing population. Total plantation area in the country was 3.32 x 10^9 m^2 in 1990, of which 1.98 x 10^9 m^2 were in the northern and eastern hill forests and 1.13 x 10^9 m^2 in coastal regions (FAO Forestry, 2003). The estimated-planted forest area in the country in 2000 was 6.25 x 10^9 m^2 (FAO Forestry, 2003) – see Table 5.2. In order to achieve a sustainable management of forest resources in Bangladesh, the Forest Master Plan (1993), developed by the Bangladeshi Ministry of Environment and Forest, suggested an annual planting target of about 1.8 x 10^8 m^2 during 1993 – 2002 and 2.1 x 10^8 m^2 during 2003 – 2012 (MEF, 1993). Potential areas for industrial plantation totaling about 7.0 x 10^9 m^2 exist in the Chittagong and Sylhet divisions (FAO Forestry, 2003).

Type of land use	Area (10^7 m^2)
Agricultural land:	
Arable land[a]	8019
Permanent crops[b]	410
Permanent pasture[c]	600
Total	9029
Forests and woodlands	1334
Urban areas and mountains	2654
Total land area	**13017**

[a] land under temporary crops; [b] crops that occupy the land for long periods and need not be replanted after harvest; [c] land used permanently (≥5 years) for herbaceous forage crops

Table 5.1 Land use in Bangladesh in 2000 (FAOSTAT, 2004; FAO Forestry, 2003)

Species group	Area of plantation		% of total area according to the type of plantation stated	
	10^7 m^2	% of total area	Industrial	Non industrial
Acacia spp.	32.0	5.1	48	52
Dalbergia	10.7	1.7	100	
Eucalyptus	37.3	6.0	48	52
Gmelina	21.3	3.4	48	52
Mahoganies	5.3	0.8	100	
Rubber	91.8	14.7		100
Teak	143.9	23.1	100	
Other broad leafed	282.5	45.2	48	52
Total	624.8	100.0		

Table 5.2 Plantation areas in Bangladesh in 2000 by species groups (FAO Forestry, 2003)

5.3 Biomass Resources

The economy of Bangladesh depends principally on agriculture. The main crops produced are rice, sugar cane, vegetables, wheat, jute, pulses, coconuts, maize, millet, cotton and groundnuts (see Table 5.3). Agricultural crops generate large quantities of residues. Such residues represent an important source of energy both for domestic as well as industrial purposes. Other sources of biomass in the country are farm-animal wastes and poultry droppings produced by the national herds (see Table 5.4), fuel wood from existing forests, tree residues, and saw dust from the forestry industry (see Table 5.5). The 138.1 million (World Bank, 2005) citizens of Bangladesh produce huge amounts of human waste and municipal solid waste (MSW) annually.

Crop	Annual production rate[a]
Rice	39.090
Sugarcane	6.838
Vegetables (total)	1.837
Wheat	1.507
Jute	792.000
Pulses (total)	345.000
Coconut	88.000
Millet	57.000
Cotton[b]	45.000
Groundnut	34.000
Maize[b]	10.000

[a] Annual production rates for rice, sugarcane, vegetables and wheat are in Mtonne/year. For the rest of the agricultural crops the production rates are in ktonne/year.

[b] Annual production of rates of cotton and maize is not available for 2003, so production rates of 2002 were used.

Table 5.3 Annual yield of agricultural crops in Bangladesh in 2003 (FAOSTAT, 2004)

Species	Number of heads (millions)
Farm animals:	
Cattle	24.500
Buffaloes	0.850
Goats	34.500
Sheep	1.260
Poultry	153.000

Table 5.4 Number of heads of national herds of farm animals and poultry in Bangladesh in 2003 (FAOSTAT, 2004)

Biomass resource	Annual production rate		Moisture content		Annual production rate
	(Mtonne)	Reference	(% by mass)	Reference	(Mtonne dry matter)
Fuel wood	6.932	FAO Forestry (2003)	20	Yokoyama et al. (2000)	5.546
Tree residues	1.821[a]	Hashem (1996)	-	-	1.821
Saw dust	0.118	Moral (2000)	20	Yokoyama et al. (2000)	0.094

[a] dry matter content

Table 5.5 Annual rates of waste generated by the forests and forestry industry in Bangladesh

5.3.1 Agricultural Residues

There are two types of agricultural-crop residues; field residues and processing residues. Studies in some neighboring Asian countries (Yokoyama et al. 2000; and Koopmans, 1998) produced useful residue-to-yield ratio for several agricultural crops. These ratios have been employed in this study, together with published productivity figures (FAOSTAT, 2004) for the individual crops (see Table 5.3), in order to estimate the rate of generation of the corresponding residues in Bangladesh (see Table 5.6).

Crop residues can be collected, mostly by bailing, either at the same time or after the primary crop has been harvested. Not all field residues are recoverable; some must be left to maintain soil quality and prevent soil erosion (Hall et al. 1993). The percentage of field residues of a crop to be recycled onto the land depends upon the specific local climatic and soil conditions (FAE, 2005). There is no available specific data concerning the common practices in Bangladesh or the neighboring Asian countries. However, in developed countries, it has been proved that only 35% of field crop residues can be removed without adverse effects on future yields (FAE, 2005). Crop-processing residues, on the other hand, have a 100% recovery factor. Accordingly, it is estimated that the total annual amount of recoverable agricultural-crop residues in Bangladesh is 41.994 million tonnes, of which 62.5% are field residues and 37.5% are process residues (see Table 5.6).

5.3.2 Animal Wastes and Poultry Droppings

Manure from cattle, goats, buffaloes and sheep are the common animal wastes in Bangladesh. The quantity of waste produced per animal per day varies depending on various factors (e.g. body size, type of feed and level of nutrition).

In 2003, total population of chicken and ducks in Bangladesh were 140 and 13 million heads respectively (FAOSTAT, 2004). There are two types of chicken, broiler and layer. Individual population data, however, is not available. Othman et al. (1996) reported that the average amount of droppings (on air-dry basis) produced by broiler and layer are 0.02 kg/bird/day and 0.03 kg/bird/day respectively. A conservative estimate of the national production rate of poultry droppings can be achieved by considering that all the chickens are of broiler type and production rate of ducks is the same as for chicken.

Biomass	Residues-to-yield mass ratio		Residues generation rate (ktonne/year)	Residues recovery rate (ktonne/year)	Moisture content		Residues recovery rate (ktonne dry matter/year)
	Value	Reference			(% by mass)	Reference	
Field residues							
Rice straw	1.695	Yokoyama et al. (2000)	66258	23190	12.7	Yokoyama et al. (2000)	20245
Wheat straw	1.75	Koopmans (1998)	2637	923	7.5	RWEDP (2002a)	854
Sugarcane tops	0.3	Koopmans (1998)	2051	718	50	Koopmans and Koppejan (1997)	359
Jute stalks	3	Koopmans (1998)	2376	832	9.5	RWEDP (2002a)	753
Maize stalks	2	Koopmans (1998)	20	7	12	RWEDP (2002a)	6
Millet stalks	1.75	Koopmans (1998)	100	35	15	Koopmans and Koppejan (1997)	30
Groundnut straw	2.3	Koopmans (1998)	78	27	12.1	Koopmans and Koppejan (1997)	24
Cotton stalks	2.755	Koopmans (1998)	124	43	12	RWEDP (2002a)	38
Residues from vegetables[a]	0.4	ICCEPT (2005)	735	257	20	ICCEPT (2005)	206
Residues from pulses[a]	1.9	ICCEPT (2005)	656	229	20	ICCEPT (2005)	184
Subtotal			75035	26261			22699
Process residues:							
Rice husk	0.267	Yokoyama et al. (2000)	10437	10437	12.4	Yokoyama et al. (2000)	9143
Rice bran	0.083	Yokoyama et al. (2000)	3244	3244	9	RWEDP (2002a)	2952
Sugarcane bagasse	0.29	Koopmans (1998)	1983	1983	49	Yokoyama et al. (2000)	1011
Coconut shells	0.12	Koopmans (1998)	11	11	8	RWEDP (2002a)	10
Coconut husks	0.41	Koopmans (1998)	36	36	11	RWEDP (2002a)	32
Maize cob	0.273	Koopmans (1998)	3	3	15	RWEDP (2002a)	3
Maize husks	0.2	Koopmans (1998)	2	2	11.1	Koopmans and Koppejan (1997)	2
Groundnut husks	0.477	Koopmans (1998)	16	16	8.2	Koopmans and Koppejan (1997)	15
Subtotal			15732	15732			13168
Total residues			90767	41994			35867

[a] due to lack of information about the types of residues, it was assumed that the residues generated from vegetables and pulses are all field based.

Table 5.6 Generation and recoverable amounts of agriculture-crop residues in Bangladesh in 2003

The annual production rates of animal wastes and poultry droppings were estimated by employing the number of heads of the national herds (see Table 5.4) and the waste generation rate per head for the individual species as estimated in neighboring Asian countries (see Table 5.7). The recovery/collection factors for animal waste and poultry droppings were considered to be 60% and 50%, respectively (Narang et al. 1999; and Othman et al. 1996). Accordingly, it is estimated that the total annual amount of recoverable animal wastes and poultry droppings in Bangladesh is 20.619 million tonnes (see Table 5.7).

5.3.3 Human Waste and Municipal Solid Waste

The total rate of human waste generation by the 138.1 million citizens (World Bank, 2005) in Bangladesh has been estimated as 4.537 million tonnes of dry matter/year (i.e. 0.09 kg/capita/day) (Narang et al. 1999). Compared with an average MSW generation rate of 0.4 kg/capita/day in Indian cities (Narang et al. 1999), in urban areas of Bangladesh the rate is between 0.4 to 0.5 kg/capita/day (REIN, 2005e). In rural areas of the country, the generation rate is only 0.15 kg/capita/day (REIN, 2005e). Estimated rural and urban population are 108.56 and 29.54 respectively (see Appendix C) in 2003. Considering that human waste and MSW are 100% recoverable, the total annual amount of the biomass available from these two sources in Bangladesh is 14.793 million tonnes (see Table 5.8).

5.3.4 Forests and the Forestry-Industry

In Bangladesh, forests are subject to heavy pressures in terms of both demands on wood production and competing land uses due to the large, increasing population. Deforestation, environmental degradation, the growing demand for traditional energy and the lack of development in the forestry sector are serious concerns for the government and the people in general. Agriculture can no longer support any more labour. Employment of the ever-increasing rural labour force is dependent on the growth of rural industries, which, in turn, are very much dependent upon the existence of a sustainable supply of biomass fuel, especially fuel wood. The forest land is unevenly distributed in 64 districts. The locations of Bangladesh forest are shown in Table 5.9. Forest biomass includes tree components such as trunk, branches, foliage and roots. Tree trunks and main branches constitute what is commonly known as fuel wood. Twigs, leaves, bark, and roots are tree residues. The total fuel wood production in Bangladesh in 2003 was 6.932 million tonnes (FAO Forestry, 2003).

Biomass	Rate of generation			Waste recovery rate (Mtonne dry matter/year)
	(kg of dry matter/head/day)		(Mtonne dry matter/year)	
	Value	Reference		
Animal waste:				
Cattle	2.86	Narang et al. (1999)	25.576	15.345
Buffaloes	2.52	Narang et al. (1999)	0.782	0.469
Goats	0.55	Narang et al. (1999)	6.926	4.156
Sheep	0.33	Narang et al. (1999)	0.152	0.091
Subtotal			33.436	20.061
Poultry droppings	0.02	Othman et al. (1996)	1.117	0.558
Total			34.552	20.619

Table 5.7 Generation and recoverable rates of animal wastes and poultry droppings

Biomass	Rate of generation[a]		Waste recovery rate	Moisture content		Waste recovery rate
	(kg/capita/day)	(Mtonne/ year)	(Mtonne/ year)	(% by mass)	Reference	(Mtonne dry matter/year)
Human waste	0.09	4.537	4.537			4.537
MSW:		0.000	0.000			0.000
Urban	0.4	4.312	4.312	45.0	REIN (2005e)	2.372
Rural	0.15	5.944	5.944	45.0	REIN (2005e)	3.269
Subtotal MSW		10.256	10.256			5.641
Total		14.793	14.793			10.177

[a] Calculation of human waste generation rate is based on dry matter.

Table 5.8 Generation and recoverable rates of human waste and MSW in Bangladesh in 2002 (Narang et al. 1999; REIN, 2005e)

Forest type	Location (district)
Mangrove forest (Tropical evergreen)	
Sundarbans	Khulna, Satkhira
Coastal	Cox's Bazar, Chittagong, Noakhali, Barishal, Patuakhali, and adjacent coastal districts
Hill forest (Tropical moist evergreen)	Chittagong, Sylhet, Comilla, Rangamati, Bandarbon, Khagrachari
Plain land sal forest (Tropical moist deciduous)	Dhaka, Tangail, Mymensingh, Dinajpur

Table 5.9 Forest type and location (Hashem, 1996)

Estimates for the rate of supply of tree residues in recent years are not available; in 1992, it was 1.821 million tonnes (Hashem, 1996). Both wood processing residues (e.g. sawmill off-cuts and sawdust) and recycled wood (e.g. that derived from the demolition of buildings, pallets and packing crates) are important sources of energy. The annual amount of such recycled wood, on a sustainable basis, is, however, not known. It has been estimated that only about 20% of a tree, initially harvested for timber, results in sawn products. The remaining 80% is discarded, in equal proportions, as forest residues and process residues (i.e. bark, slabs, sawdust, trimmings and planer shavings) (Koopmans, 1998). Ply mills produce about the same amount of residues as sawmills (Koopmans, 1998). In 1998, 0.118 million tonnes of sawdust was available for energy purposes (Moral, 2000). Considering 100% recovery rate, the annual amount of recoverable biomass from forests and forestry-industry in Bangladesh is 8.871 million tonnes (see Table 5.6).

5.4 Total Energy Potential of Recoverable Biomass Resources

The total annual generation and recoverable rates of biomass in Bangladesh is 148.983 and 86.276 million tonne/year, respectively (see Table 5.10). Agricultural residues represent 48.7% of the total recoverable biomass, followed by a 23.9% contribution from animal wastes and poultry droppings. Using the lower calorific values of the individual biomass components, the energy potential of the annually recoverable 86.276 million tonnes of biomass is estimated at 1125.345 PJ (or 26.794 mtoe) (see Table 5.11), which is equivalent to 312.596 TWh.

Biomass resource	Rate of generation (Mtonne/year)	Waste recovery rate (Mtonne/year)	Waste recovery rate (Mtonne dry matter/year)
Crop residues:			
Field residues	75.035	26.261	22.699
Process residues	15.732	15.732	13.168
Animal wastes and poultry droppings	34.552	20.619	20.619
Human wastes and MSW	14.793	14.793	10.177
Forests and Forestry-industry	8.871	8.871	7.461
Total	148.983	86.276	74.124

Table 5.10 Annual generation and recoverable rates of biomass from different sources in Bangladesh

Biomass	Recovery rate (ktonne/year)	Recovery rate[a] (ktonne dry matter/year)	Lower calorific value		Energy content (PJ)
			(GJ/tonne)	Reference	
Field crop residues :					
Rice straw	23190	20245	16.30	Yokoyama et al. (2000)	329.994
Wheat straw	923	854	15.76	RWEDP (2002a)	13.459
Sugarcane tops	718	359	15.81	Koopmans (1998)	5.676
Jute stalks	832	753	16.91	RWEDP (2002a)	12.733
Maize stalks	7	6	14.70	RWEDP (2002a)	0.088
Millet stalks	35	30	12.38	Koopmans (1998)	0.371
Groundnut straw	27	24	17.58	Koopmans and Koppejan (1997)	0.422
Cotton stalks	43	38	16.40	RWEDP (2002a)	0.623
Residues from vegetables	257	257	13.00	ICCEPT (2005)	3.341
Residues from pulses	229	229	12.80	ICCEPT (2005)	2.931
Subtotal	**26261**	**22699**			**369.638**
Process crop residues :					
Rice husk	10437	9143	16.30	Yokoyama et al. (2000)	149.031
Rice bran	3244	2952	13.97	Koopmans (1998)	41.239
Sugarcane Bagasse	1983	1011	18.10	Koopmans (1998)	18.299
Coconut Shells	11	10	18.53	Koopmans (1998)	0.185
Coconut husks	36	32	18.53	Koopmans (1998	0.593
Maize cob	3	3	14.00	RWEDP (2002a)	0.042
Maize husks	2	2	17.27	RWEDP (2002a)	0.035
Groundnut husks	16	15	15.66	Koopmans and Koppejan (1997)	0.235
Subtotal	**15732**	**13168**			**209.659**
Total agricultural-crop residues	**41994**	**35867**			**579.297**
Other biomass :					
Animal waste	20061	20061	13.86	Parikh and Ramanathan (1999)	278.045
Poultry droppings	558	558	13.50	Othman et al. (1996)	7.533
Human waste	4537	4537	10.60	RWEDP (2002a)	48.092
MSW	10256	5641	18.56	RWEDP (2002a)	104.697
Fuel wood	6932	5546	15.00	RWEDP (2002a)	83.190
Tree residues	1821	1821	12.52	Hashem (1996)	22.799
Saw dust	118	94	18.00	RWEDP (2002a)	1.692
Total					**1125.345**

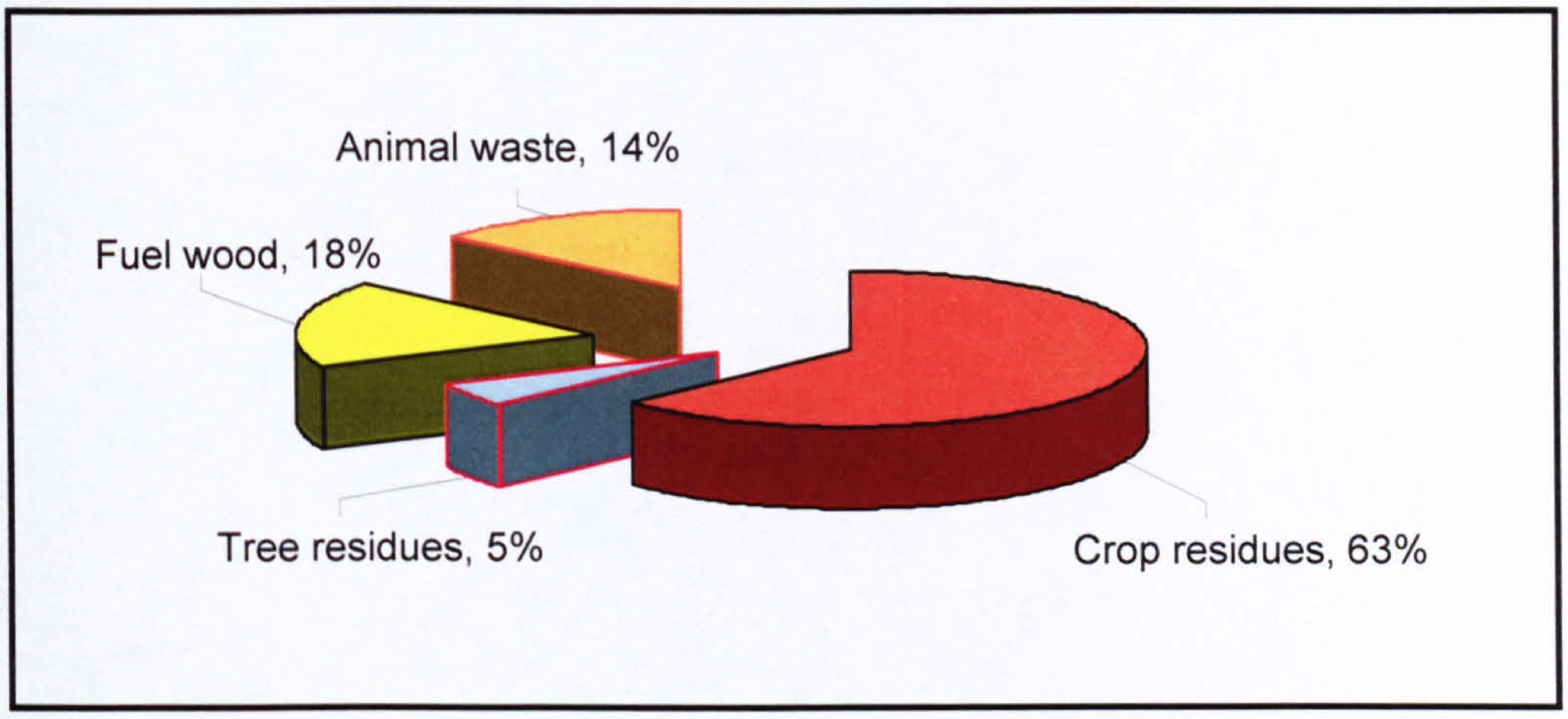
[a] moisture content are 20% by mass for residues from vegetables and pulses

Table 5.11 Energy potential of biomass resources in Bangladesh

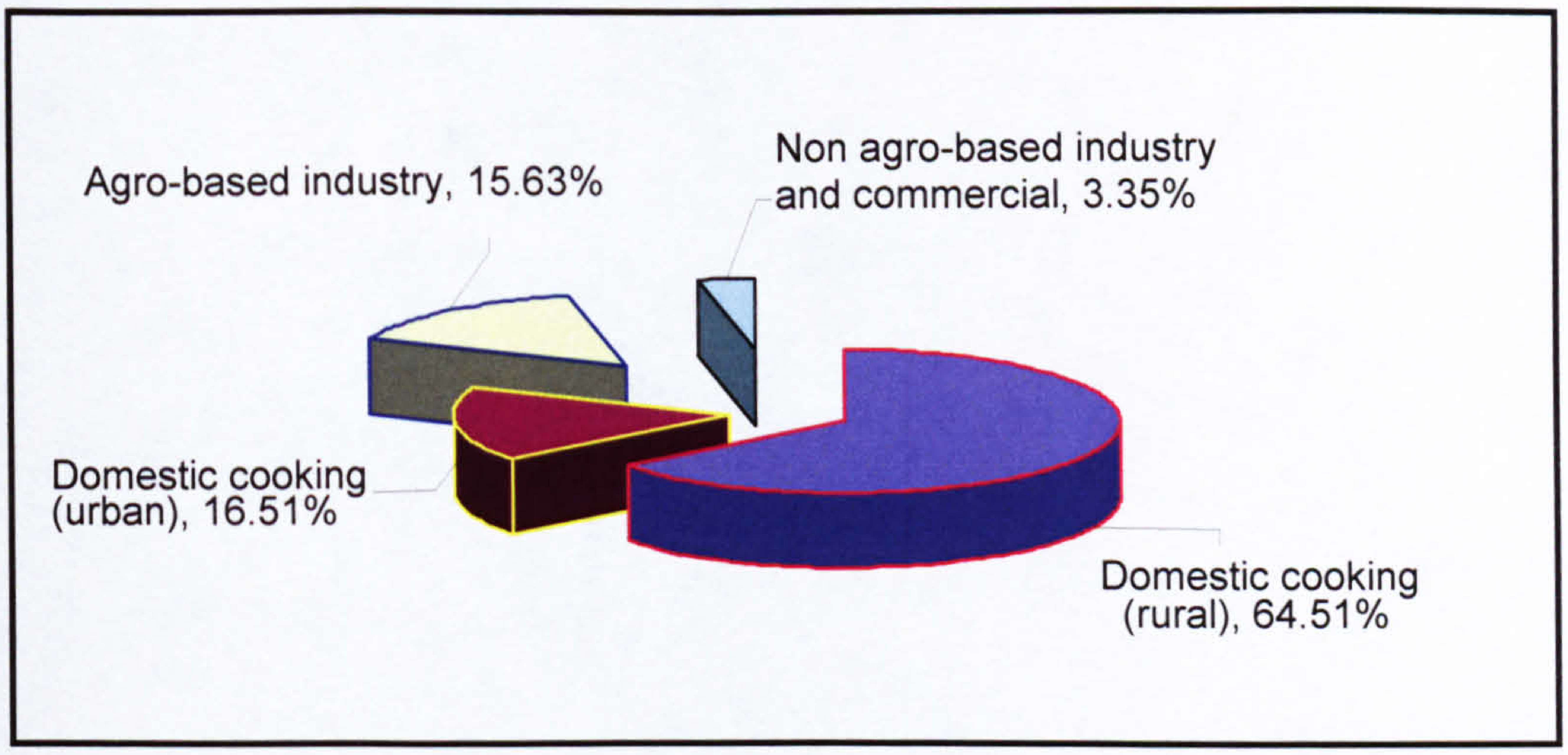
5.5 Biomass Consumption

In Bangladesh, biomass is used as an energy source as well as for non-energy purposes. It is widely utilised in both rural and urban areas of the country, as a domestic fuel for cooking and heating. Many commercial and industrial facilities employ biomass for the provision of process heat. In addition, some quantities of biomass are used as animal fodder, animal bedding, building material, material for furniture making, and as an organic soil conditioner (i.e. fertiliser). There is no available data for the rates of biomass consumption for these non-energy uses. It is, however, believed that the amount of biomass involved represents a small proportion of the total consumption figure, and, therefore, will not be considered in this study.

The pattern of utilisation of biomass for energy varies according to the region of the country, the prevailing socio-economic conditions and the availability of commercial fuels (Alam, 1991; and Biswas and Lucas, 1997a). Figure 5.1 presents estimates for the annual rates of consumption of biomass for energy in Bangladesh.



(a) According to biomass source



(b) According to consumer sector

Figure 5.1 Biomass consumption for energy in Bangladesh (Bose, 1996)

Domestic cooking, particularly in rural areas, represents the largest single consumer of biomass. Table 5.12 presents statistical data for total biomass energy consumption in some developing countries in Asia. Although the use of biomass energy per capita in Bangladesh exhibited an average decreasing trend between 1981 and 1991 and was below the regional average in 1991, the total biomass consumption has increased as a result of the rapid population growth. Many other developing Asian countries have experienced similar trends (RWEDP, 1997).

5.6 Biomass Energy Available for Electricity Generation

5.6.1 Whole Country

In 1991, the biomass consumption for energy was 276.6 PJ (or ~ 6.6 Mtoe) (see Table 5.12). At an average annual growth rate of 1.3% (see Table 5.12), the consumption in 2003 was estimated to be 319.75 PJ (or ~ 7.613 Mtoe). The total available recoverable biomass energy of the country in 2003 was estimated as 1125.345 PJ, which is equivalent to 26.794 Mtoe (see Table 5.11). Accordingly, in 2003, 805.595 PJ or 223.776 TWh of biomass energy was available for the generation of electricity. In 1998, the total biomass energy consumption was estimated at 435.204 PJ (or ~ 10.362 Mtoe) (RWEDP, 2002a). Assuming the same average annual growth rate of 1.3%, the biomass consumption in 2003 would be 463.492 PJ (or ~ 14.484 Mtoe). This is equivalent to 3.356 GJ/capita/year. Based on this estimate, the amount of biomass energy available in 2003 was 661.853 PJ, which is equivalent to 183.848 TWh. Considering that the consumption of biomass for non-energy purposes is negligible, the annual available biomass energy potential in Bangladesh, varies from 183.848 to 223.776 TWh, for electricity generation in 2003.

Country	Population (millions)	GDP (US$/capita)	Biomass annual consumption rate					
			Total		Per capita		Per unit of GDP	
			(PJ)	Average annual growth rate (%)	(GJ/capita)	Average annual growth rate (%)	(GJ/ US$)	Average annual growth rate (%)
Bangladesh	116.4	176	276.6	1.3	2.4	-1.2	13.5	-2.7
Bhutan	1.6	200	11.7	4.8	7.4	2.6	37.2	-1.6
Cambodia	8.6		5.4	2.7	0.6	0.0		
China	1170.7	337	2017.8	2.7	1.7	1.2	5.1	-5.9
India	862.7	370	2823.7	2.7	3.3	0.6	8.8	-2.4
Indonesia	187.7	523	1464.8	2.2	7.8	0.2	14.9	-3.1
Lao PDR	4.3	310	38.5	2.8	8.9	-0.1	28.7	
Malaysia	18.3	2449	90.2	2.7	4.9	0.0	2.0	-3.3
Myanmar	42.7	243	192.8	2.1	4.5	0.0	18.5	1.0
Nepal	20.1	166	205.7	6.2	10.2	3.3	61.6	1.6
Pakistan	121.5	341	296.2	4.4	2.4	1.1	7.1	1.5
Philippines	63.8	596	381.8	2.2	6.0	-0.3	10.0	1.0
Sri Lanka	17.4	455	89.4	2.5	5.1	1.0	11.3	1.6
Thailand	55.4	1334	526.4	0.8	9.5	-0.6	7.1	6.6
Vietnam	68.1	721	250.8	2.4	3.7	0.3	5.1	

Table 5.12 Biomass energy consumption in some Asian developing countries in 1991 and the average annual rate of growth in the period 1981 – 1991 (RWEDP, 1997)

5.6.2 District wise

In previous section, total amount of biomass available for electricity generation in 2003 has been estimated for the whole country. District wise availability of the biomass resources are needed to model the sustainable small to medium-scale biomass electricity plant for off-grid decentralized electricity generation in Bangladesh. District wise generation rates are not available for all types of agricultural crops, considered in section 5.3. District wise generation rates of rice, wheat, jute, sugarcane, vegetables and pulses are available for year 1998 (see Appendix C). District wise rural and urban population and number of farm-animals and poultry heads are available for year 1998 and 1996 respectively (see Appendix C). In this study, district-wise population, generation rates of agricultural crops, and number of farm-animals and poultry heads has been estimated for year 2003 (see Appendix C), using the following relationship:

$$W_{\mathrm{d\,in\,2003}} = \frac{W_{\mathrm{t\,in\,2003}} * W_{\mathrm{d\,in\,1998}}}{W_{\mathrm{t\,in\,1998}}}$$

where

$W_{\mathrm{d\,in\,2003}}$ Generation rates of agricultural crops/number of farm animals and poultry/urban or rural population in a district, in 2003

$W_{\mathrm{t\,in\,2003}}$ Generation rates of agricultural crops/number of farm animals and poultry/ urban or rural population in the whole country, in 2003

$W_{\mathrm{d\,in\,1998}}$ Generation rates of agricultural crops/number of farm animals and poultry/ urban or rural population in a district, in 1998/1996

$W_{\mathrm{t\,in\,1998}}$ Generation rates of agricultural crops/number of farm animals and poultry/ urban or rural population in the whole country, in 1998/1996

There is no district wise biomass generation data from forests and forestry industry. District wise forestry area is available for 1998 (see Appendix C). District wise generation rates of biomass from forests and forestry industry in 2003 were estimated by assuming that the residues are proportional to the forested areas in the individual districts and that such area remain unchanged during the period 1998 – 2003 (see Appendix C).

Same methodology, which was used for the whole country, has been adopted to estimate the district wise availability of the biomass resources for electricity generation. Distribution of the number of heads of individual species of the farm animals are not available by districts (see Appendix C). As a conservative estimate, waste generation rate of per head buffalo was used as the waste generation rate of cattle and buffaloes together. Similarly, waste generation rate of per head of sheep was used as the waste generation rate of goats and sheep together. District wise biomass consumption rate data is not available. National rate of the biomass consumption data (i.e. 3.356 GJ/capita/year) has been used for estimating the district wise biomass availability, assuming that the difference between the national average rate of biomass consumption and rate of biomass consumption in any district is negligible. Figure 5.1 (a) was used to estimate the source wise biomass availability in any district. The biomass availability of districts Serajganj and Pabna is shown in Table 5.13. The negative figures of forestry residues indicate shortages. The reasons for choosing these two districts are their highest total biomass energy potential. Biomass availability for any other district has been estimated - see Appendix B and Appendix E.

Type of biomass resources	Serajganj		Pabna	
	Ktonne dry matter/year	PJ/year	Ktonne dry matter/year	PJ/year
Farm animal waste	240.10	3.328	224.23	3.108
Poultry droppings	10.73	0.145	8.40	0.113
MSW	107.16	1.989	95.48	1.772
Human excreta	96.49	1.023	81.28	0.862
Agricultural waste	6957.83	113.590	6150.22	100.813
Forests and forestry-industry residues	-151.12	-1.773	-127.32	-1.495
Total[a]	**7261.19**	**118.300** (32.861)	**6432.28**	**105.173** (29.215)

[a] figures within the bracket represents the biomass energy in TWh/year

Table 5.13 Biomass available for electricity generation in district Serajganj and Pabna

5.7 Biomass Savings

In many developing countries, the efficiency of utilisation of biomass in traditional systems is very low. Tables 5.14 and 5.15 present reported figures for the efficiencies of typical household stoves used in Asia. A large amount of biomass can be saved annually in the country by using improved (i.e. more efficient) cooking stoves, furnaces, boilers and other devices consuming biomass fuels. Bhattacharya et al. (1999) estimated total biomass saving potential of 322 million tonnes annually, through efficiency improvement of biomass energy utilization, in selected seven Asian countries - India, Pakistan, Nepal, Philippines, Sri Lanka and Vietnam. Of the total savings, domestic cooking represents highest biomass savings, of about 152 million tonnes of fuel wood and 101 million tonnes of agricultural residues (Bhattacharya et al. 1999).

The traditional mud cooking stoves used in Bangladesh exhibit overall efficiencies of only between 5 and 10% (Banu, 1996). A number of improved stoves have been developed at the IFRD of BCSIR. These have been classified as (Banu, 1996):

- improved stoves without chimney, which save 50-55% fuel compared to the traditional stove;
- stoves with chimney, with a fuel saving of 60-65% ; and
- stoves with waste heat recovery.

Fuel	Combustion efficiency (%)	Overall efficiency (%)
Biogas	99	57
LPG	98	54
Kerosene	98	50
Fuel wood	90	23
Crop residues	85	14
Dung	85	11

Table 5.14 Efficiencies of typical household stoves in South Asia (RWEDP and UNEP, 2000)

Type of stove	Biomass fuel	Combustion efficiency (%)	Heat transfer efficiency (%)	Overall efficiency (%)
Open and three stone fire places	Fuel wood	90 – 92	20	18
Solid stoves with or without chimney	Fuel wood	80 – 91	15 – 29	14 – 24
	Agricultural residues	77 – 90	11 – 14	10 – 14
	Animal waste	82 – 89	10	9
Portable ceramic or pottery stoves	Fuel wood	89	33	29
	Agricultural residues	86	22	19
	Charcoal	85	20	17
	Animal waste	88	15	13
Portable ceramic/metal stoves	Fuel wood	91	24 – 29	21 – 26
	Agricultural residues	91	24	22

Table 5.15 Efficiencies of household stoves in India (TERIIN, 2003)

IFRD has been engaged in a pilot-scale dissemination of improved model biomass-fired stoves, capable of saving 50 – 70% of fuel compared with the traditional stoves all over the country (Banu, 1996). These improved stoves are gradually gaining popularity.

Biomass briquettes have the main advantages of easy transportation, better handling, cleaner and more efficient combustion, and higher volumetric calorific value of the fuel. It also produces a fuel that is suitable for a variety of applications. Briquetting of sawdust and other agro-residues has been practised for many years in several countries. Briquettes can be produced with a density of 1200 to 1400 kg/m^3 compared with a corresponding value of 500 – 700 kg/m^3 for common wood. Accordingly, the savings of diesel oil during the transportation of residues or wood are substantial: a 10 tonnes truck can transport 3 - 4 times more weight of briquette than loose biomass fuel (Grover, 1995). There are two types of machines used for briquetting the biomass; these are piston press (also called die and punch) and screw extruder. The screw extruder technology was successful in briquetting rice husk and saw dust in Europe, Japan, Malaysia, Taiwan and Thailand (Babu and Yuvaraj, 2001). The machines operating in Bangladesh are of heated-die screw extruder type (Moral, 2000).

5.8 Seasonal Availability of Biomass Resources

Agricultural crops considered in this study are rice, wheat, Jute, sugarcane, vegetables and pulses. Three different types of rice grow at different seasons in Bangladesh, whereas jute and sugarcane grows once a year. Agricultural residues are available only at the time of harvest. Harvesting starts soon after the crop ripens. Different types of vegetables and pulses grow in Bangladesh throughout the year. It was assumed that the residues from vegetables and pulses are not seasonal dependent. The seasonal availability (see Table 5.16) of rice, wheat, jute and sugarcane are:

- **Rice.** The local names of three different types of rice are: Amon, Aush, and Boro. Amon is the monsoon crop; Boro is the winter crop; and Aush are the short pre-monsoon crop. The harvesting time of rice in different seasons are: Aush (July – August), Amon (November – January), and Boro (April – May).
- **Wheat.** Annual crop in Bangladesh, the planting period of wheat is November – December and the harvesting period is March – April.

- **Jute.** Jute is cultivated in the rainy season. Planting of jute usually starts at the end of February and continues till end of May, depending on the species. About four months after planting, harvesting begins (i.e. July to September).
- **Sugarcane.** Sugarcane keeps the land occupied throughout the year. Cane is harvested by cutting down the plant stalk. In Bangladesh, the harvesting season of sugarcane extends from October to March.

There are some months when availability of biomass is less than the average quantity throughout the year and on the other hand there are some months when the availability of the biomass is higher than the average. Storage of agricultural crop residues are required, if a biomass electricity plant is designed based on the average availability.

5.8.1 Storage of Biomass Resources

There are two types of fuel storage systems, these are: open and covered storage systems. In open systems, the biomass fuel is stored either directly on the ground or on a concrete pad. The covered systems can include plastic on slab (or on ground), open sheds, closed sheds, silos, and air bags (Perlack et al. 1995). During designing of storage facility, the following factors must consider (Perlack et al. 1995 and Junginger, 2000):

- the distance to the conversion plant
- physical and chemical properties of the biomass fuel
- seasonal weather conditions and operational requirements of the plant

Type of residues	Seasonal Availability / Harvesting Period											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Rice (Boro) residues (straw,husk,bran)				✓	✓							
Rice (Aman) residues (straw, husk, bran)	✓										✓	✓
Rice (Aush) residues (straw, husk, bran)							✓	✓				
Wheat straw			✓	✓								
Jute stalk							✓	✓	✓			
Sugarcane tops and bagassee	✓	✓	✓							✓	✓	✓

Table 5.16 Seasonal availability of agricultural crop wastes by month in Bangladesh

5.8.2 Impact of Biomass Storage

For a biomass-based electricity generation plant with storage facility, it is very important to asses the viability of the storage facility of biomass. The main impacts to consider are:

- **Economics.** The parameters of economics are: cost of land, construction cost of the storage facility area, repair and maintenance costs. Construction of the facility is related to the properties of biomass. Another important thing to consider is that whether the storage area/facility can cope during the natural calamities (floods, storms) or not, which are common in Bangladesh.
- **Safety and security.** When arranging such type of facility one should also consider safety hazards which might cause. The main safety hazard to consider is fire. For some types of biomass, if it is kept open, the heat of sun might cause fire. This fire may spread the surrounding areas as well. Security is another issue to consider. If the biomass storage facility is located in an area where there is a shortage of biomass, then people might steal the biomass from the storage facility.
- **Operating conditions.** Temperature and timing/period of the storage of biomass are very important to monitor. There might be some decomposition losses during the storage period (Perlack et al. 1995). Decomposition losses would be higher if the storage period is longer, but due to unavailability of these losses data, it can be assumed negligible for this study.
- **Environmental.** For some type of wet biomass, odour might generate due to the storage. There is no odour, if the biomass is dry.

5.9 Conclusions

Estimation of division-wise and district-wise biomass energy availability is important for assessing decentralised biomass electricity generation potential and economics. A methodology to estimate national and district-wise biomass generation, recovery and availability rates (both annual, seasonal or monthly) for electricity generation in Bangladesh, has been presented in this chapter.

The study indicates that in 2003, the national total annual generation and recoverable rates of biomass in Bangladesh were 148.983 and 86.276 Mtonnes, respectively. Of the total recoverable amount, agricultural residues represent 48.7%, followed by a 23.9% contribution from animal wastes and poultry droppings. In energy terms, the national annual amount of the recoverable biomass is equivalent to 312.596 TWh. Considering the present national consumption of biomass; the total available biomass resources for electricity generation vary from 183.848 to 223.776 TWh. The results obtained show that all districts, with the exception of Dhaka, has considerable amount of available resources of animal wastes, poultry wastes, MSW and human excreta. Currently, not all districts have the potential to utilise agricultural and forestry residues for electricity generation.

A large amount of biomass can be saved by employing improved (i.e. more efficient) cooking stoves, furnaces, boilers and other devices consuming biomass fuels. The traditional mud cooking stoves used in Bangladesh exhibit overall efficiencies of only between 5 and 10%. So, with the implementation of the ongoing improved-stoves installation program of the GOB and utilisation of more energy efficient devices, it is expected that most districts will have a considerable amounts of these residues for electricity generation. In 2003, Serajganj had the highest total biomass availability potential of 32.861 TWh, followed by Pabna with 29.215 TWh. Biomass availability by division has been presented in Appendix F. Biomass availability by districts (of khulna division) has been shown in Appendix E.

CHAPTER 6

FEASIBLE TECHNOLOGIES, INVESTMENT COSTS, CONVERSION EFFICIENCIENCY AND ELECTRICITY GENERATION POTENTIAL

6.1 Technically Feasible Conversion Technologies and Methodology

The utilisation of biomass fuel is a proven option for the small to medium-scale decentralised generation of electricity. Different types and sizes of biomass-based decentralised electricity generation has been practising in neighbouring countries such as India, Pakistan, Thailand, Sri Lanka, Nepal, China, Philippines and Indonesia. The technologies used in these countries are mainly anaerobic digestion, gasification and direct combustion. Amongst the neighbouring countries, India and China has vast experience of using these technologies for many years.

Anaerobic digestion is a commercially proven technology. Digesters of various types and sizes are widely distributed in India and China. Biomass gasification is normally practised at a relatively small scale, but systems exist for power output capacities of up to 50 MW_e (RWEDP, 2002a). TERIIN (2004) reported that a gasifier system can reduce fuel consumption by half and also helps in replacing 70-80% of the consumption of diesel oil of commonly employed diesel generators, resulting in reduced diesel imports. Commercial biomass gasifiers are now available in different sizes. Gasifiers have been manufactured locally in India, China, Thailand and Indonesia (RWEDP, 2002a).

Direct-fired biomass power plants have been installed in a number of countries in Asia. These plants have the option to deliver electricity to the grid, utilise the electricity to satisfy the power demand of a stand-alone production process, or a combination of both. In neighbouring Indonesia and Thailand, co-generation is normally practised in sugar factories, palm oil industry, and rice mills (RWEDP, 2002a). These industries have the potential to produce electricity in excess of their normal heat and power demand, which can be fed to the grid.

After reviewing the biomass electricity plants, presented in Appendix D, it is concluded that in developing countries, gasification-based biomass electricity generation technologies are more practised than the anaerobic digestion-based or direct combustion-based electricity generation technologies. Different types of Biomass-to-electricity conversion technologies are studied (see Chapter 3). Considering the technical knowledge of the rural population in Bangladesh, and examining the installed biomass electricity generating plants (Appendix D); the feasible technologies for small to medium-scale, off-grid biomass based electricity generation in Bangladesh are in the order of:

- Gasification
- Anaerobic digestion
- Direct combustion

Table 6.1 shows the types of biomass and the energy conversion equipment for the three feasible technologies for small-to-medium scale electricity generation.

Conversion technology	Biomass resource		Equipment
	Type	Examples	
Gasification	Dry to moist solid biomass	Agricultural residues, wood/forestry residues, poultry litter and MSW	Reciprocating engine Gasifier, Furnace, Boiler Steam turbine, Micro Gas turbine
Anaerobic digestion	Moist to wet biomass	Manure, sewage sludge, MSW	Reciprocating engine Digester, Furnace, Boiler Steam turbine, Micro Gas turbine
Direct combustion	Mainly dry solid biomass	Agricultural residues, wood/ forestry residues, and MSW	Reciprocating engine Furnace, Boiler, Steam turbine

Table 6.1 Small to medium-scale biomass to electricity generation technologies

Reciprocating engines are of two types:

- Internal combustion engines. The different types of ICEs are: spark ignition engine and compression ignition engine.
- External combustion engines. Types of external combustion engines are: Stirling engines and Steam engines.

In this chapter, trends in capital investment costs and overall electricity generation efficiency of the feasible technologies are established from collated information of systems operating in both developing and developed countries (see Appendix D). All the cost figures were adjusted for year 2004 value. Cost data of any currency (other than US$) and for a specific year, was first converted to the US$, using the currency conversion factor for that year. A currency converter tool, Bank of Canada (2004), was used for this purpose. The converted value was adjusted to US$ in 2004, using the consumer price index (CPI) inflation calculator (BLS, 2004) of U.S. Department of Labour. The CPI inflation calculator calculates current value of US$ amounts from years ago or the value of current US$ in an earlier period.

Generated best fit lines equations were used for plant sizing and for economical analysis. In some cases, data available from developing countries were not enough; best fit line generated for the developed countries was modified to use for the developing countries, by comparing the other technologies for which adequate data for both the developed and developing countries are available.

Diesel generators are used all over the world for the small-scale, off-grid electricity generation. Electricity generation plants employing dual-fuelled (diesel and biogas or producer gas) engines represent attractive options, because of the operational flexibility. To compare the economics of the different types of electricity generation plants, best fit lines for diesel and dual-fuelled engines electricity generation systems are also developed.

Figure 6.1 shows the methodology used for developing the costs and efficiency correlations and estimating the electricity generation potential for all types of feasible technologies. The different steps of the methodology are:

- Conversion suitability and relevant properties of available biomass resources were discussed for each type of feasible conversion technologies. Available biomass resources were grouped for variety of biomass fuels with varying degree of moisture content for assured fuel supply and maximum electricity potential, without adversely affecting the efficiency, costs and reliability.

- District wise and national total recoverable amount of biomass were estimated in Chapter 5. Energy potentials were calculated for each technology option, using the heating value of the biogas generated (in the case of anaerobic digestion technology option) and lower calorific value (for combustion and gasification technology option) of biomass resources.
- Using the biomass electricity plants data presented in Appendix D, trends for specific capital investment cost and overall electrical efficiency of the different technologies were generated. Mean conversion efficiencies data were estimated. Finally, electricity generation potential were estimated, using the mean conversion efficiency data of each technology option.

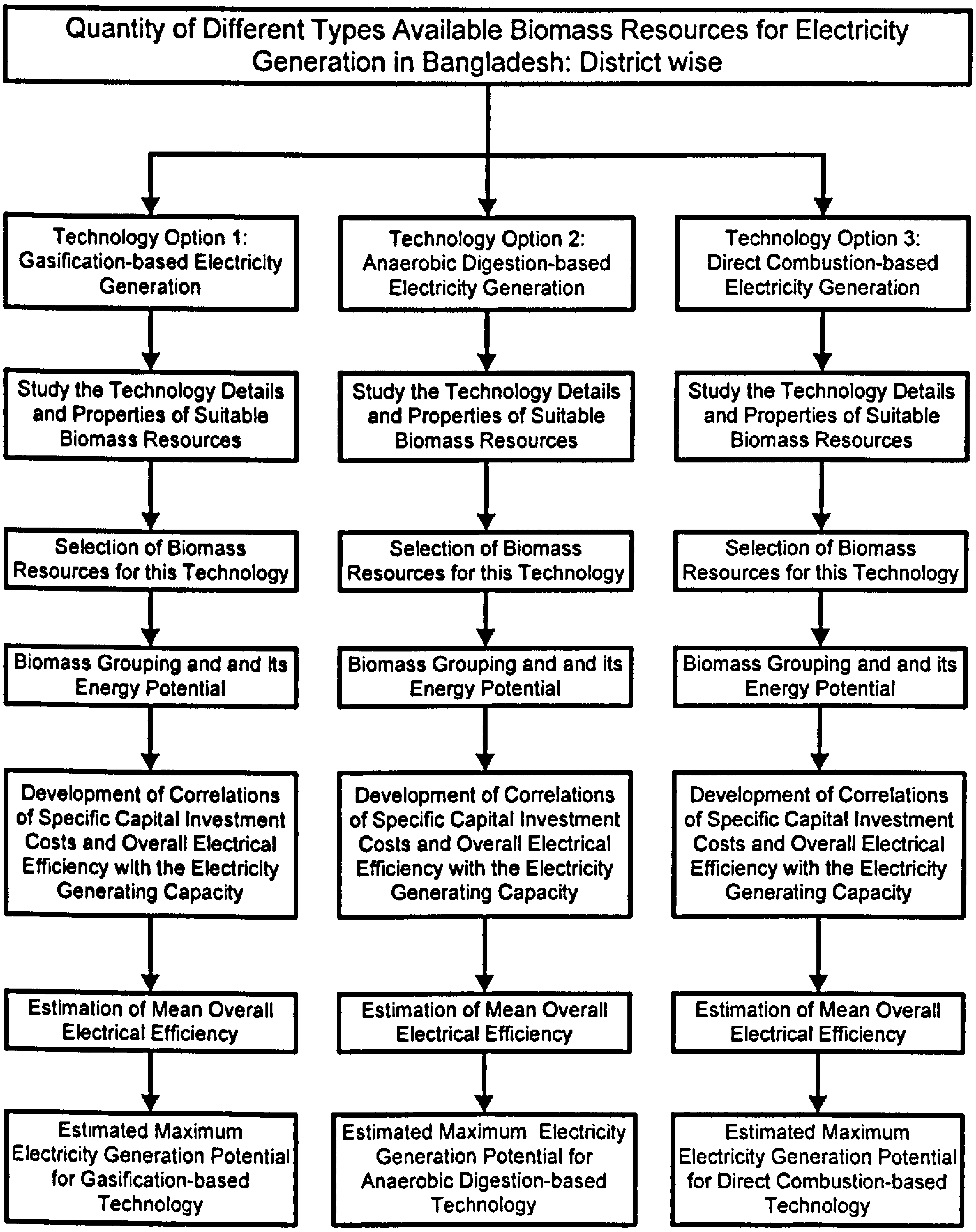


Figure 6.1 Methodology: energy and electricity potential

6.2 Gasification

Gasification system consists of a reactor or gasifier into which biomass fuel is fed along with a limited (less than stoichiometric) supply of air. Heat for gasification is generated through partial combustion of the feed biomass fuel. Producer gas consists of a mixture of H_2, CO, CH_4, CO_2 and N_2; of which CO_2 and N_2 are non-combustible gases. Producer gas contains significant amount of tars, soot, ash and water (Stassen, 1995).

6.2.1 Properties of Biomass for Gasification and Combustion

The important properties of biomass fuel for gasification and direct combustion are (Quaak et al. 1999; Wereko-Brobby and Hagan, 1996; Turare, 1997; Schmidt and Pinapati, 2000):

- Moisture content. Moisture content is expressed as a percentage of the biomass weight. The biomass weight can be determined to on a wet basis, dry basis, or dry-and-ash-free basis. Moisture content of biomass, on a wet basis, varies from less than 10% for straw to 50-70% for forestry biomass. High moisture content in biomass reduces reactor (for both in combustion and gasification) thermal efficiency, due to the requirement of additional fuel drying energy. The maximum allowable moisture content is 55% on wet basis, to ignite the biomass fuel. Moisture content level of about 20% and below is recommended for satisfactory combustion efficiencies. Biomass with moisture content of 5-30% by mass is gasifiable. For trouble free and economical operation of the gasifier, moisture content below 15% by mass is desirable.

- Energy content or heating value. The most acceptable form of biomass fuel heating values for combustion and gasification purposes is lower heating values with specific reference to the actual moisture content of the fuel.

- Ash content. Ash is the inorganic part of biomass which remains in oxidized form after combustion or gasification of biomass fuel. Ash content is expressed in the same way as moisture content. However, ash content is commonly expressed on a dry basis. Both the total ash content and the composition of the ash in the biomass are important. The ash composition affects the system's operation under high temperature combustion and gasification. Melting and agglomeration of ashes in reactor causes slugging and clinker formation, which leads to excessive tar formation or complete blocking of reactor. No slugging occurs with fuel having ash content below 5%. Wood chips contain 0.1% ash, while rice husk contains high amount of ash (16-23%). Ash is high in alkaline materials like potassium, sodium, calcium and magnesium. The land filling of ash affects the land usage and also the environment for its corrosive nature.

- Reactivity of the fuel. The reactivity is defined as the rate of reduction of carbon dioxide to carbon monoxide. Fuels such as wood, charcoal and peat are far more reactive than coal. Reactivity influences the reactor design, as it dictates the height needed in the reduction zone. A number of elements, which act as catalysts, have a positive effect on the rate of gasification. For example, small quantities of potassium, sodium and zinc have a large effect on the reactivity of the fuel.

- Particle size and size distribution. Size of the fuel affects the pressure drop across the reactor. The pressure drop is essential to draw the air and gas through gasifier. Large sizes of particles give rise to reduced reactivity of fuel, causing start-up problem and poor gas quality. In general, for wood gasification wood chips ranging from 10x5x5 mm to 80x40x40 mm is preferable.

- Bulk density of the fuel. It is defined as the weight per unit volume of loosely tipped fuel. For biomass fuels it is expressed either on an oven dry weight basis (moisture content is zero) or as it is basis. Fuels with high bulk density are advantageous because they represent a high energy-for-volume value. Consequently, these fuels need less storage space. Low bulk density fuels sometimes give rise to insufficient flow under gravity, resulting in low gas heating values. Bulk densities can be increased by briquetting.
- Total solids and Volatile matter content. The term total solid is defined as the weight of the dry matter of a sample of biomass fuel, and expressed as a percentage of the weight of the wet biomass. Volatile matter is defined as the portion of dry biomass that is released when biomass is heated up to 400~500^{0}C. High volatile matter content produces more tar, which causes problems to the operation of the prime mover. Amount of the volatile matters in the biomass fuel determines the design of reactor for removal of tar. Typically, biomass has a volatile matter content of up to 80% by mass, whereas, coal has a low volatile matter content of less than 20% by mass.

6.2.2 Technology

Figure 6.2 shows the different components of the gasification-based electricity-generation technology.

6.2.2.1 Types of Gasifiers

There are two types of gasifiers: fixed bed gasifier; and fluidized bed gasifier

6.2.2.1.1 Fixed bed Gasifier

Fixed bed gasifiers are of three types: Updraft or Counter-current, Downdraft or Co-current, and Cross-draft. The selection of the type of gasifier unit will depend on the end use of the gas, the scale of operation and its feedstock.

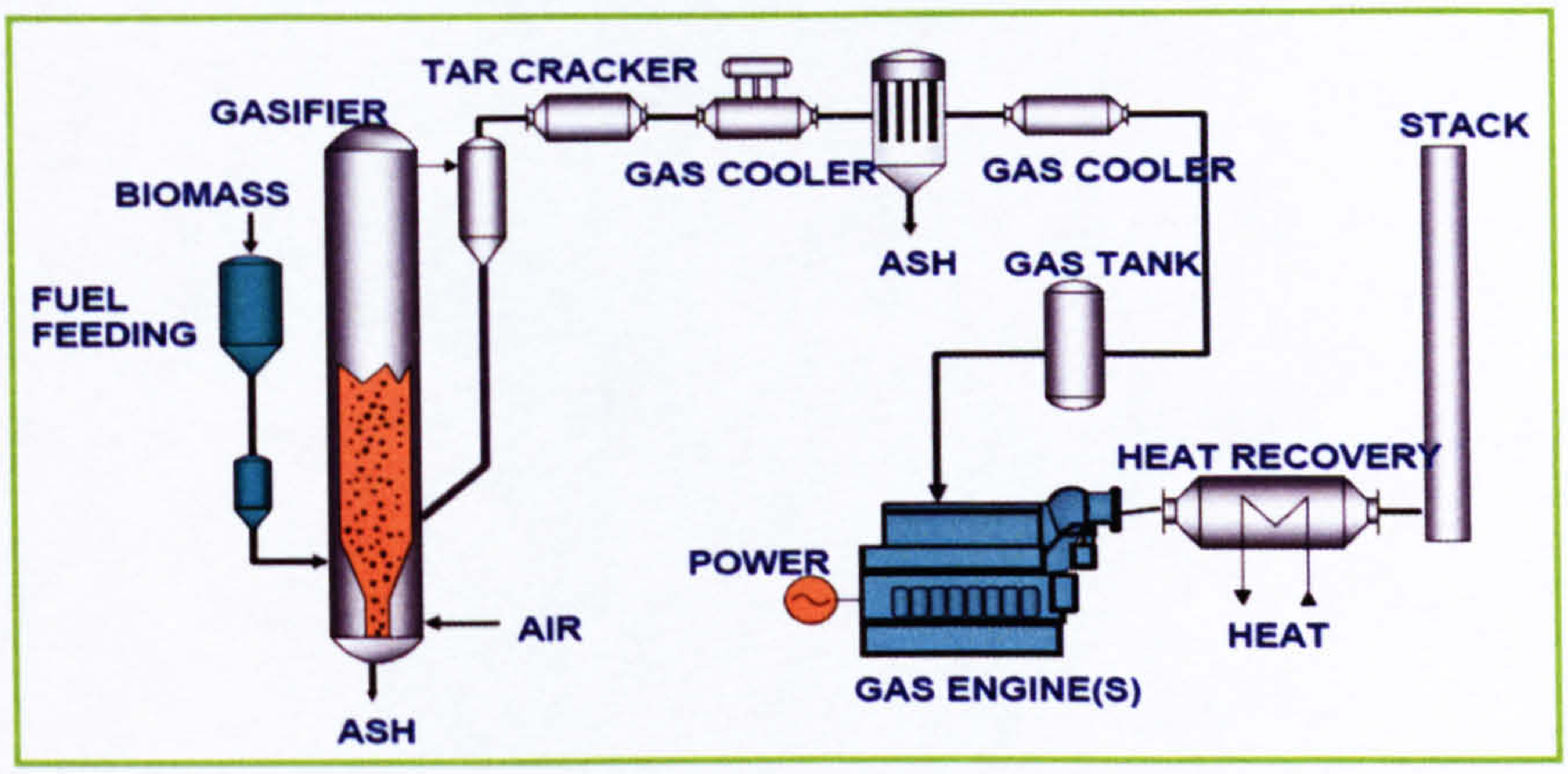


Figure 6.2 Schematic diagram of the biomass gasifier- based electricity generation (Bain, 2004)

Updraft gasifier. Biomass is fed at the top of the reactor and moves downward as a result of its conversion and removal of ashes. Air enters at the bottom and the gases produced pass upwards and exit near the top (see Figure 6.3). One of the big advantages is, the biomass fuel is dried up due to the internal heat exchange. Fuels with high moisture content (up to 60% wet basis) can be used in updraft gasifier (Quaak, et al. 1999).

Downdraft gasifier. Air and the producer gas flow downward (see Figure 6.3). Normally, these types of gasifiers have a constriction called throat to create a high temperature zone for adequate tar cracking and are mostly used for running internal combustion engines. The advantages of this type of gasifier are: reduced amount of the tar fraction in the product and shorter contact times. The disadvantages are: more uniform fuel sizes are required and are not suitable for operation with feed sizes less than 15 mm and above 50 mm, moisture content of the feed biomass must be less than 25% by mass (Wereko-Brobby and Hagan, 1996; Quaak et al. 1999).

Cross-draft gasifier. Figure 6.4 shows the schematic diagram of the cross-draft gasifier. This type of gasifier can be used for small-scale application. The drawback is, its minimal tar converting capability (Quaak et al. 1999).

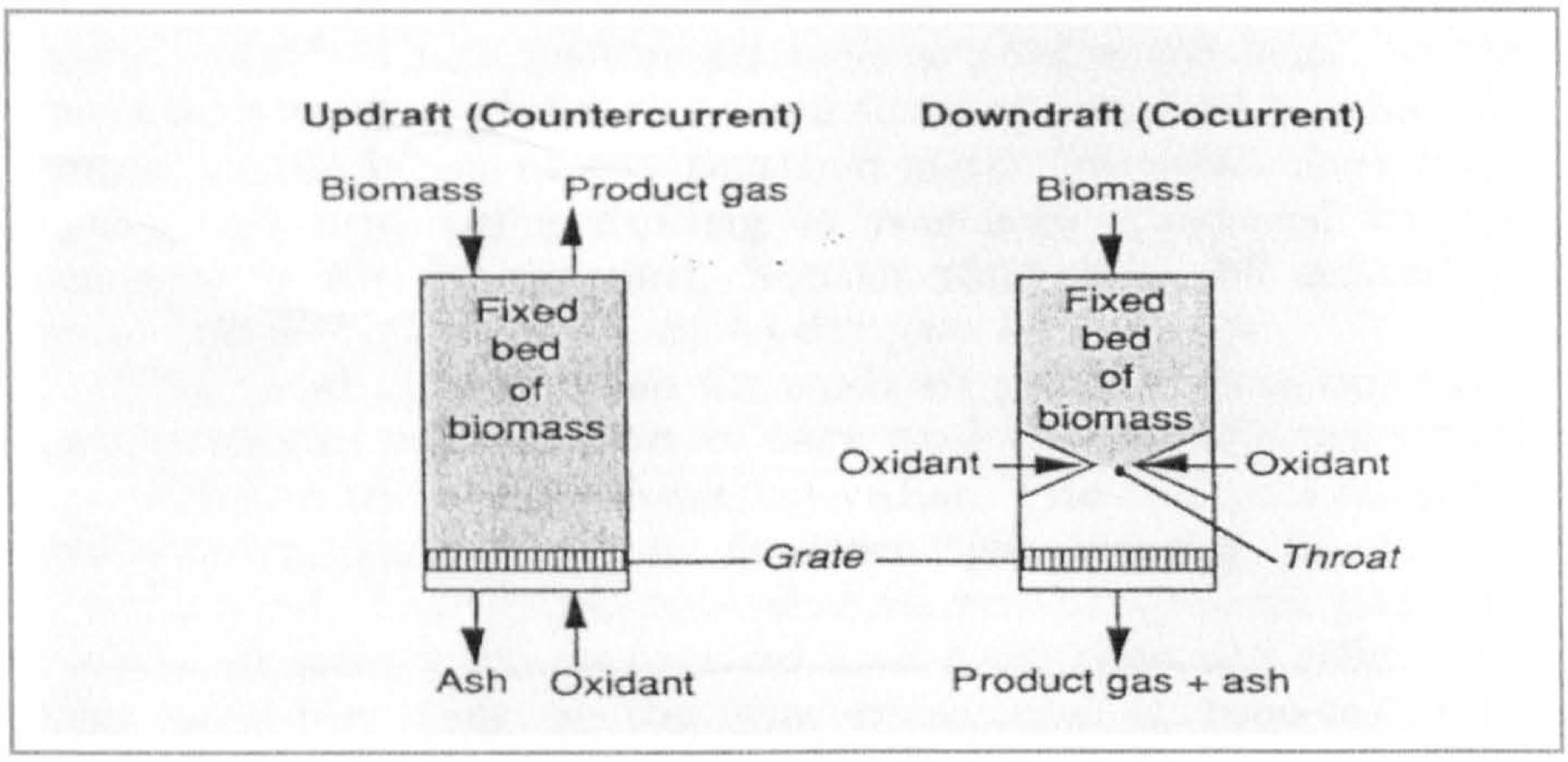


Figure 6.3 Updraft and downdraft gasifiers (Bridgwater, 1995)

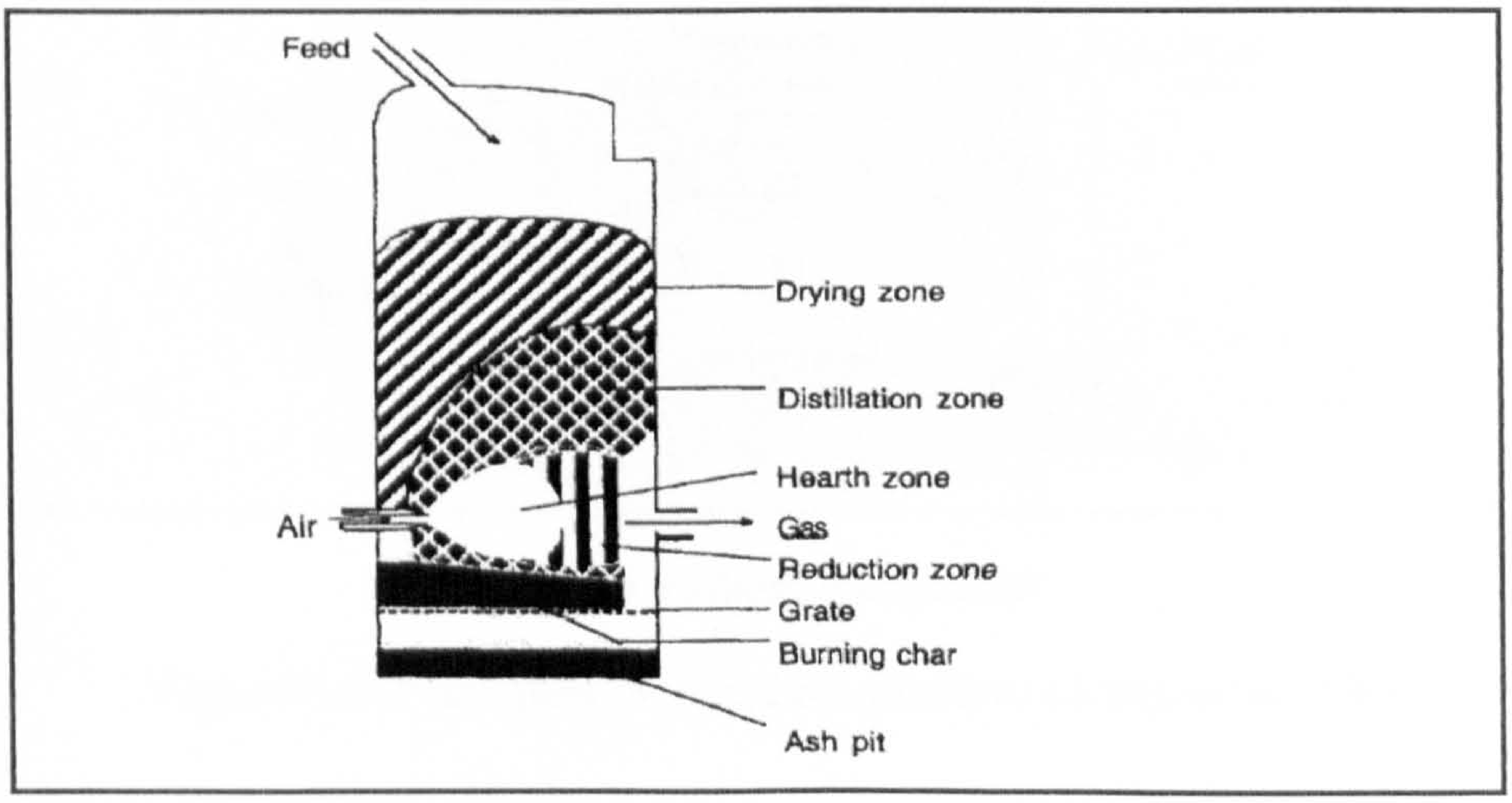
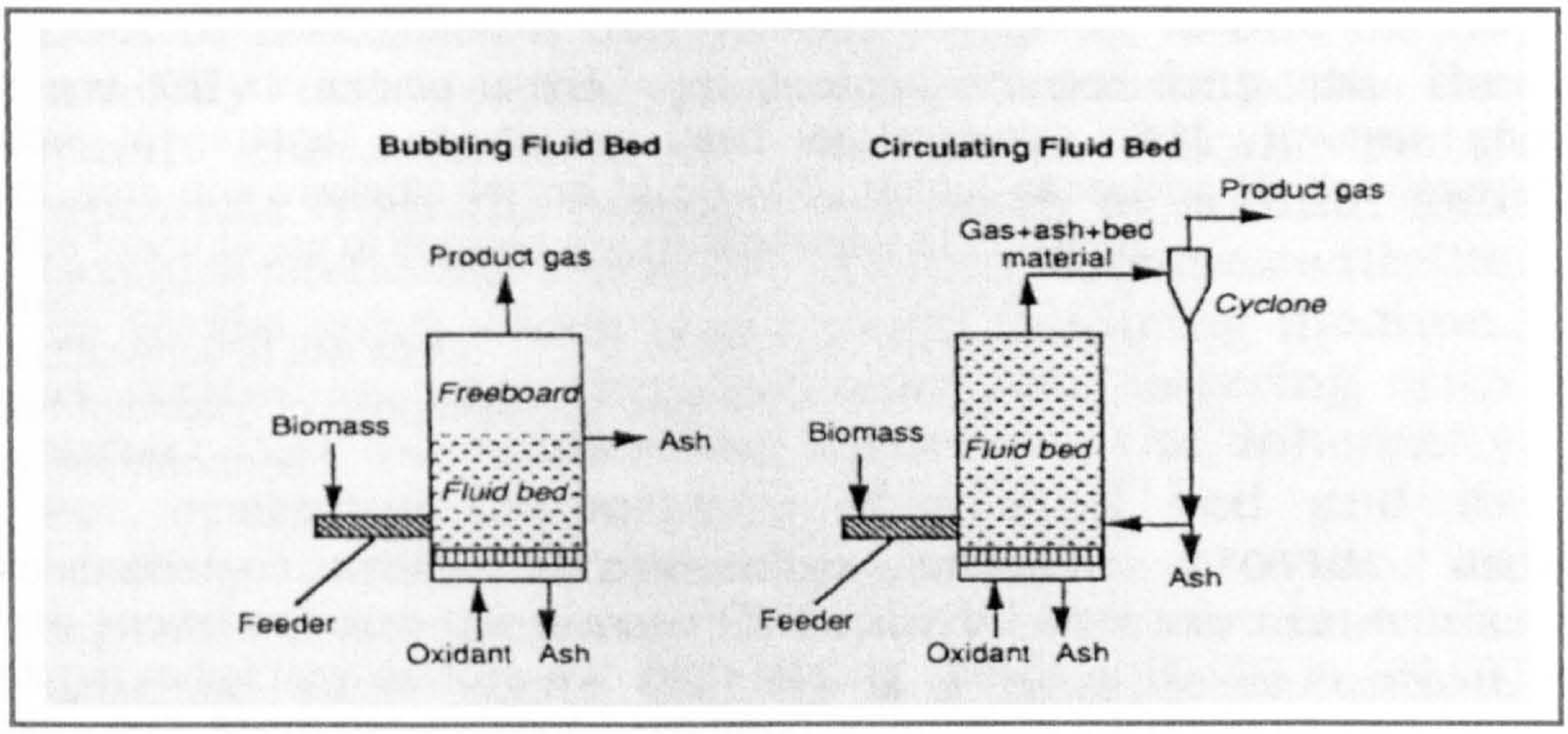


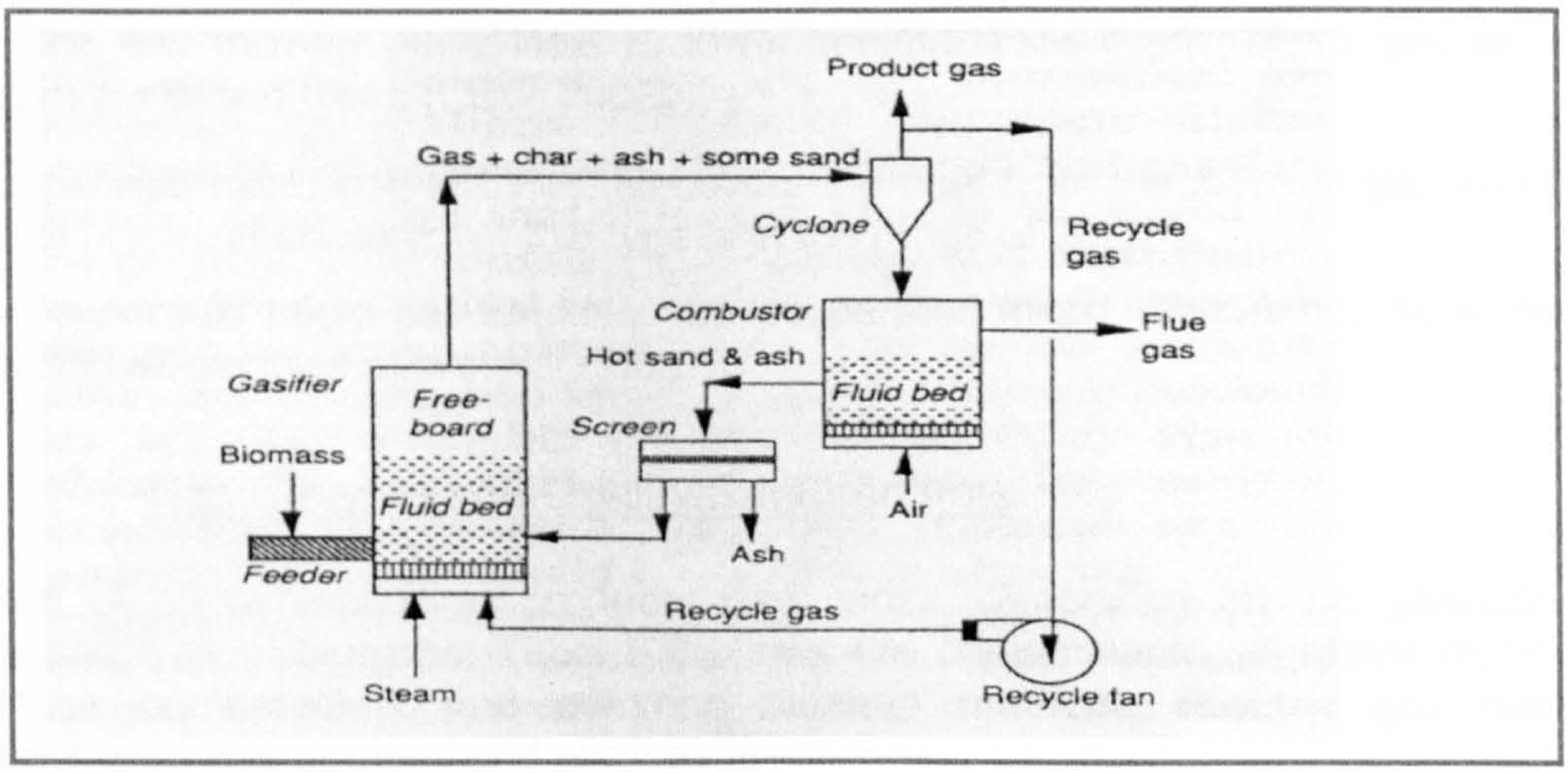
Figure 6.4 Cross-draft gasifier (Quaak et al. 1999)

6.2.2.1.2 Fluidised bed Gasifier

Fluidised bed gasifier (see Figure 6.5) was developed to overcome the operational problems of fixed bed gasification of fuels with high ash content (Quaak et al. 1999). Biomass fuel is fed into a suspended (bubbling fluidised bed) or circulating (circulating fluidised bed) hot sand bed. The fluidizing velocity in the circulating fluid bed is high enough to entrain large amount of solids with the product gas. The fluidizing material is usually silica sand, although alumina and other refractory oxides have been used to avoid sintering, and catalysts have also been used to reduce tars and modify product gas composition (Bridgwater, 1995). Twin fluidized bed gasifier is used to produce a gas of higher heating value (Bridgwater, 1995).



(a) Bubbling and circulating fluidised bed gasifiers



(b) Twin fluidized bed gasifier

Figure 6.5 Principles of fluid bed gasifiers (Bridgwater, 1995)

The advantages and disadvantages of fluidized bed gasifiers in comparison to fixed-bed gasifiers are (Quaak et al. 1999):

Advantages:

- Compact construction due to intensive mixing in the bed.
- Flexibility to change in moisture and ash content.

Disadvantages:

- High tar and dust content of the producer gas.
- Complex operation because of need to control the supply of both air and fuel simultaneously.

6.2.2.2 Prime movers

Gasifier and ICE or turbine is the most acceptable option for biomass electricity generation. In general, turbines are used for large-size plant. However, engine-generator sets are available for up to 50 MW_e output capacities (Bridgewater et al. 1998). The advantages of engines are (Bridgewater et al. 1998):

- Robustness;
- high efficiency at low sizes;
- higher tolerance to contaminants; and
- easy maintenance

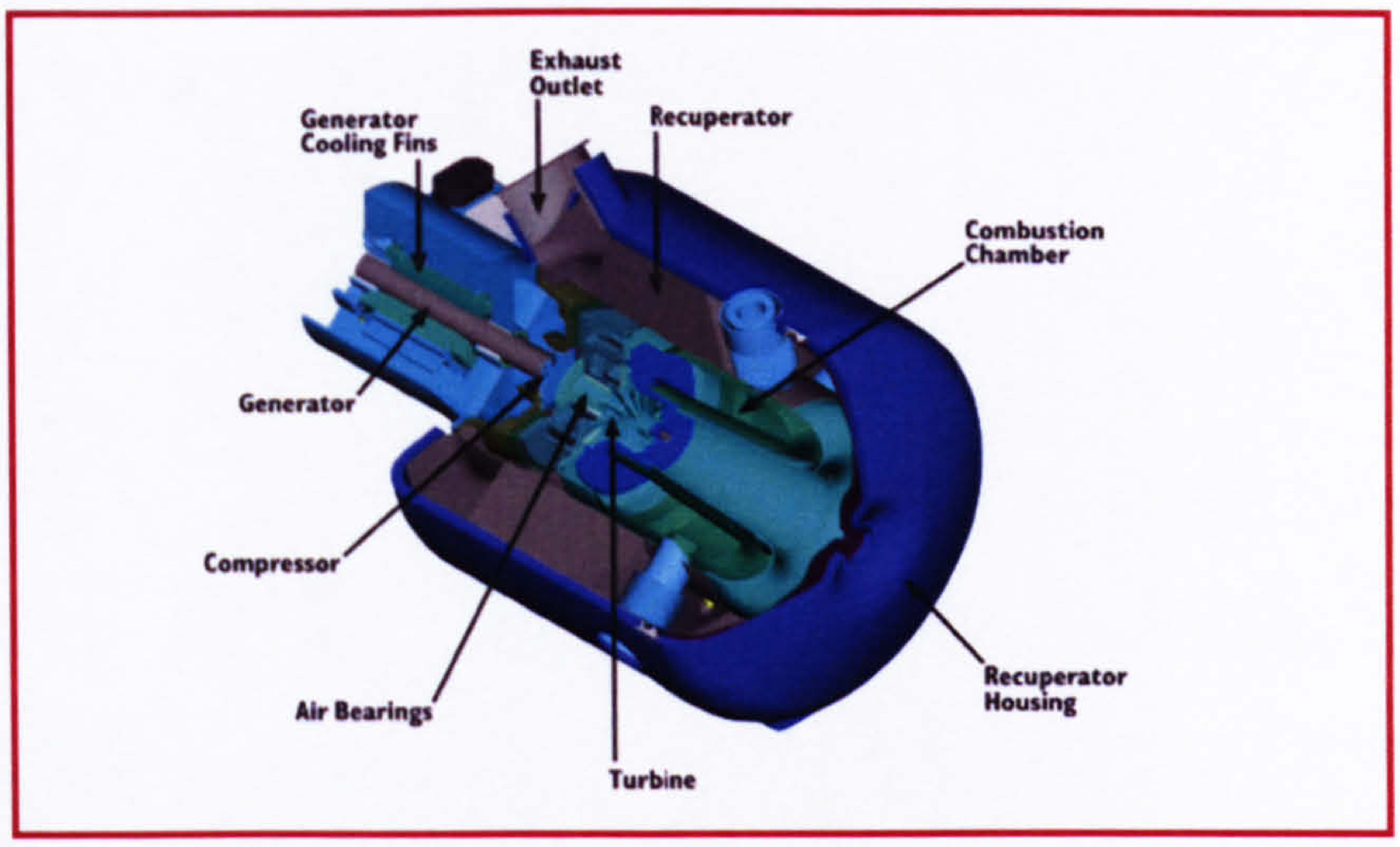
Small combustion gas turbines that produce between 25 kW and 500 kW of electrical power are known as micro gas-turbines (CEC, 2002b). Most micro gas-turbines are single-stage; radial flow devices with high rotating speeds of 90,000 to 120,000 rpm (see Figure 6.6). Micro gas-turbines have good potential as the prime movers for small-scale decentralised electricity generation. The advantages of micro gas-turbines include: compact design, small number of moving parts, light weight and good efficiencies in CHP application (CEC, 2002b; Lensu and Alakangas, 2004). Compact design and few moving parts lead to lower maintenance costs. Micro gas-turbine generators are of two types (CEC, 2002b):

- Recuperated micro gas-turbines. Recovers the heat from the exhaust gas and the overall electrical efficiency of this type is in the range of 20-30%.
- Un-recuperated micro gas-turbines. Un-recuperated micro gas-turbines have lower electrical efficiencies at around 15%.

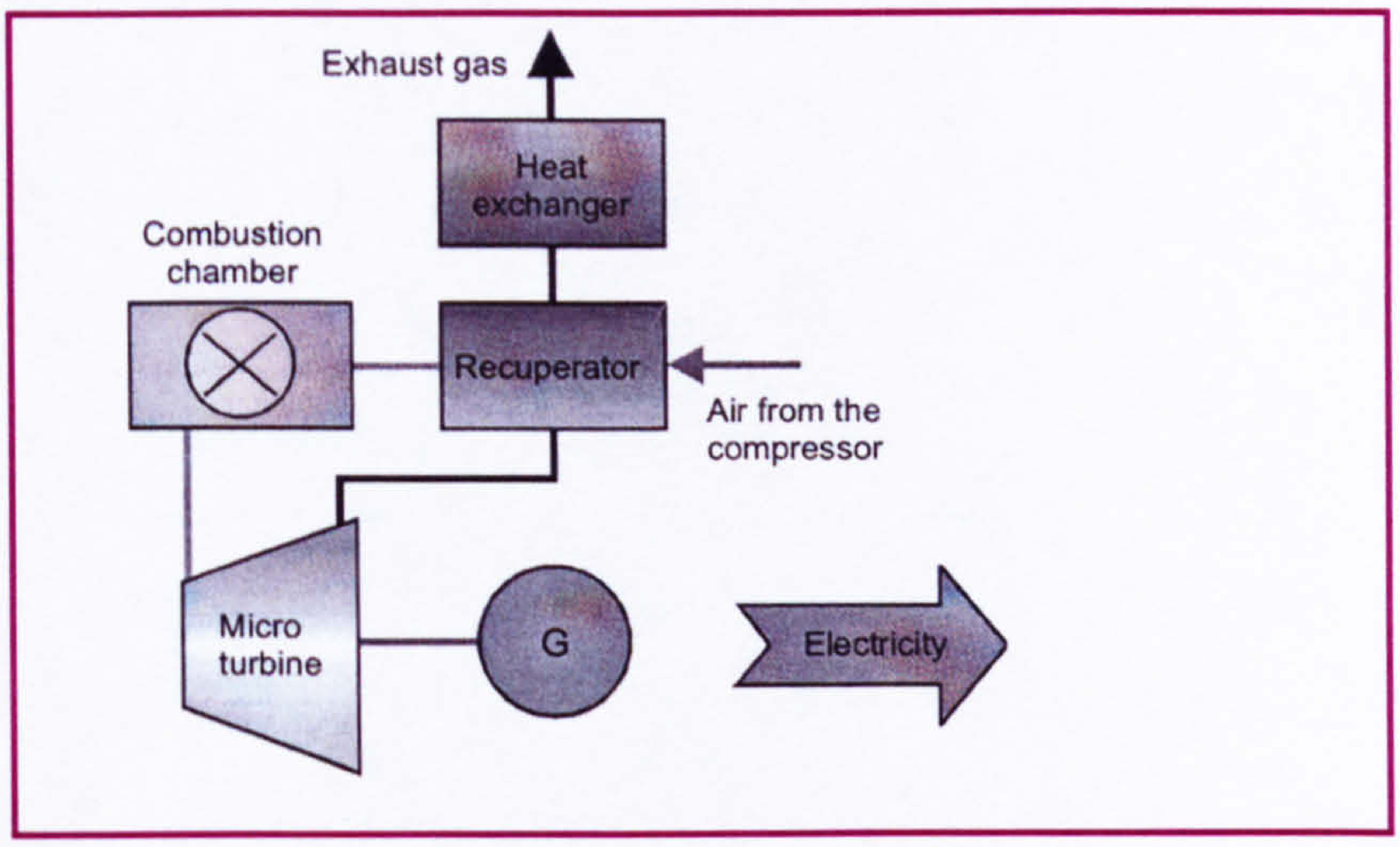
6.2.2.3 Gas Cleanup and Quality Requirements

The level of contamination in producer gas varies, depending on the gasification process and type of biomass. Table 6.2 shows the contaminants, problems resulting from these contaminants and common cleanup methods. Product gas quality requirements for gas turbines and engines are:

For Turbine Operation. Product gas specifications to use as turbine fuel are summarised in Table 6.3. Alkali metals and sulphur pose major problems. Presence of 0.1% sulphur (by weight) in the biomass fuel, can lead to levels of sulphur in the producer gas of up to 100 ppm by weight and this level is not acceptable and will require reduction (Bridgwater, 1995). Tars are a potential problem if the gas has to be compressed (Bridgwater, 1995).



(a) Physical construction



(b) Process diagram

Figure 6.6 Micro gas-turbine (Lensu and Alakangas, 2004)

For ICE Operation. The engines have the advantage of having a higher tolerance to contaminants than gas turbines (see Table 6.4). Tar present in the producer gas can condensate and clog the gas supply lines and the gas-air mixtures; accumulate on the engine intake valves; and can lead to frequent changing the spark plugs, piston rings and cylinder liner. (Quaak et al. 1999; Bridgewater et al. 1998). Acids present in the poducer gas may cause severe corrosion and affect the properties of the lubricating oil (Bridgwater, 1995).

Contaminant	Examples	Problems	Cleanup method
Particulate	Ash, char, fluid bed material	Erosion	Filtration, scrubbing
Alkali metals	Sodium and potassium compounds	Hot corrosion	Cooling, condensation, filtration, absorption
Fuel nitrogen	Mainly NH_3 and HCN	NO_x formation	Scrubbing, SCR[a]
Tars	Refractory aromatics	Clog filters, difficult to burn, deposit internally	Tar cracking, tar removal
Sulphur, chlorine	H_2S, HCL	Corrosion, emissions	Lime or dolomite scrubbing or absorption

[a] selective catalytic reduction

Table 6.2 Producer gas contaminants and cleanup processes (Bridgwater, 1995)

Producer gas characteristics		Value
Lower heating value (MJ/m^3)		4-6
Minimum gas hydrogen content (% vol.)		10-20
Maximum alkali concentration (ppb by weight)		20-2000
Maximum temperature of producer gas (°C)		450-600
Tars at delivery temperature		All in vapour form or none
NH_3		No limit
HCl (ppm by weight)		<0.5
S (H_2S + SO_2 etc.) , (ppm by weight)		<1
N_2		No limit
Combinations:	Total metals (ppm by weight)	<1
	Alkali metals + sulphur (ppm by weight)	<0.1
Maximum particulates (ash, char etc.), in ppm by weight at particle size (μm) of:		
	>20	<0.1
	10-20	<1.0
	4-10	<10.0

Table 6.3 Producer gas fuel specifications for turbines (Bridgwater, 1995)

Contaminants	Tolerance level
Dust (mg/m^3 gas)	< 50 (preferably 5 mg/m^3 gas)
Tars (mg/m^3 gas)	< 500
Acids (mg/m^3 gas)	< 50 (measured as acetic acid).

Table 6.4 Product gas contaminants tolerance level for ICEs (FAO, 1986)

6.2.3 Application

Biomass Technology Group (BTG) developed a farm-scale poultry dropping gasifier system in the Netherlands, including novel gas cleaning technology, for CHP applications. Fresh poultry droppings are prepared in batches of 3 m^3 and dried to 85% dry matter content before entering the gasifier. The producer gas is used in an internal combustion engine. Main features are (BTG, 2004):

Capacity	: 60 kW$_e$ + 100 kW$_t$
Overall electrical efficiency	: 30%
Annual poultry waste consumption	: 900 tonnes (40% MC)
Type of gasifier	: Bubbling fluidised bed
Temperature of gasification	: 700^0 C

MSW (as collected) with 20% (by wet) moisture content has a lower heating value of roughly 13 MJ/kg and has high ash content (10-12%) compared to coal (5-10%) (Klein, 2002). Combustible parts of MSW can be converted into gaseous fuel. After removing the non-combustible materials, the remaining MSW is shredded to size of less than 50 mm (Kumar, 2000). The moisture content of the feed to gasifier is maintained below 20% to maximise the heat recovery (Kumar, 2000). Figure 6.7 shows the schematic diagram MSW gasification-based electricity-generating plant.

CFB gasifiers are used for biomass electricity generation in China (see Table 6.5). Table 6.6 shows the performance of a CFB gasifier used in China. The most common types of gasifiers used in India are open top down draft gasifiers (Bharadwaj et al. 2000). A total of 42.8 MW_e biomass-gasifier electricity-generating capacity so far been installed in India (Mukhopadhyay, 2004). Plants with an output capacity of up to 500 kW_e are manufactured in India and are now being exported to Asia, Latin America, Europe and the USA (Mukhopadhyay, 2004). In China, 150 sets of biomass gasifier-electricity generation plants are in operation. The installed capacity of these plants are in the range of 200 – 1500 kW_e (Leung et al. 2004).

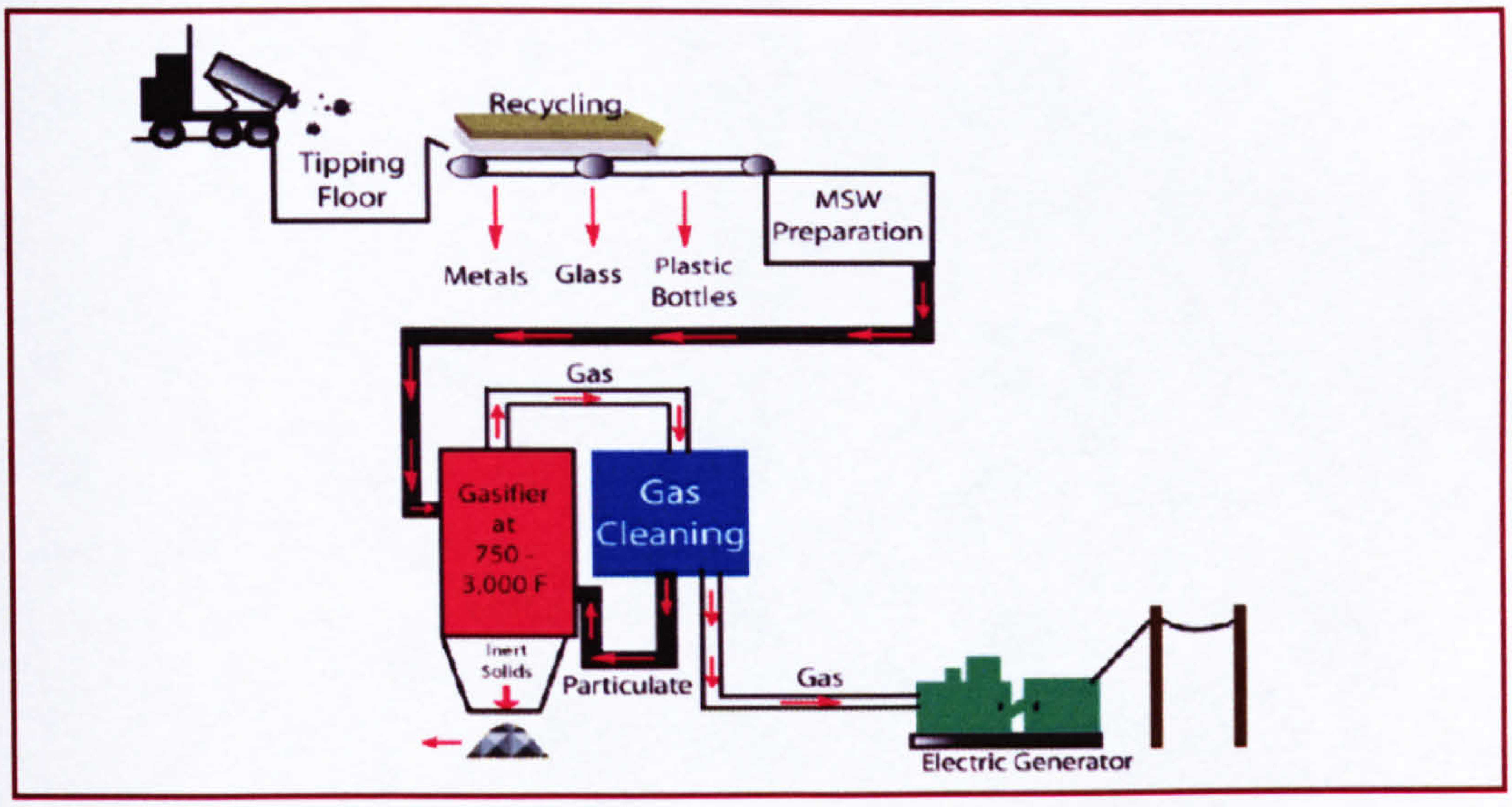


Figure 6.7 Schematic diagram of a MSW gasification-based electricity-generating plant (AES, 2004)

	Type of gasifier			
	Up-draft	Open core	Down-draft	Circulating fluidised bed
Fuel type	Tree bark, timber blocks	Rice husk	Rice and corn straw	Rice and corn straw, rice husk, saw dust
Electricity-generating capacity (kW)	2 - 30	60 - 200	60 - 200	400 - 2000
LHV of gas (MJ/ m^3)	4.1 – 5.3	3.8 – 4.6	3.8 – 4.6	4.6 – 6.3
Gasification temperature (^{0}C)	~1100	700 - 800	~1000	650 - 850
Efficiency of Gasifier[a] (%)	70 - 75	50	75	65 - 75
Application	Boiler fuel	Electricity generation	Domestic cooking	Boiler fuel and electricity generation

[a] cold gas efficiency

Table 6.5 Gasifiers and their applications in China (Leung et al. 2004)

Gasifier parameter and product gas	Parameter values and product gas characteristics		
Feed rate of fuel wood (kg/h)	1500.00	885.00	885.00
Feed rate of air (m^3/h)	1650.00	1350.00	1610.00
Gasifier temperature (^{0}C)	775.00	800.00	940.00
Gas composition (% by volume)			
H_2	7.59	6.33	7.04
CO	24.83	18.66	18.29
CH_4	13.00	11.57	13.76
C_2H_4	5.91	5.58	3.63
C_2H_6	0.30	0.11	0.60
C_2H_2	0.27	0.27	0.55
N_2	48.00	51.80	56.00
Lower heating value of gas (MJ/m^3)	6.36	5.30	5.01

Table 6.6 Performance of CFB gasifier as a function of feed rate and temperature of gasification (Wu et al. 2002)

6.2.4 Potential Biomass Resources

Gasifiers can be used for each individual type of resources, or a mixed biomass resources (see Table D1, in Appendix D). In the former type of gasification, the producer gas can be collected and stored at a central receiver from different gasifiers. The gas from the central storage could be used for electricity generation. Co-gasification of agricultural wastes, forestry residues, refuse derived fuel (RDF) and coal has been reported (Hotchkiss et al. 2002; Table D1 of Appendix D). Co-gasification of agricultural wastes and forestry residues is widely practiced (see Appendix D). Preparation of RDF from MSW involves extra costs, to make it suitable as a recipe for co-gasification with agricultural wastes and/or forestry residues. Co-gasification of biomass (agricultural wastes, forestry residues and RDF-fuel) with coal has been practiced for large scale electricity generation plants. No commercial experience of combining coal with agricultural wastes (and forestry residues) or MSW as a feedstock is available for small-to-medium scale plants (Hotchkiss et al. 2002).

Producer gas can be co-fired in the existing coal-fired plant, which has been deployed successfully in Finland and in the Netherlands (Faaij, 2006). Co-firing of producer gas with natural gas in a natural gas-fired plant is yet to be demonstrated (Faaij, 2006).

The potential biomass resources for gasification-based electricity generation systems in Bangladesh are:

- Agricultural wastes
- Forestry residues
- Poultry droppings
- Combustible parts of MSW

For most types of biomass, the HHV, on a dry and ash free basis is in the order of 20.4 MJ/kg (± 15%) (Quaak et al. 1999). Other properties of the biomass fuels such as moisture content, bulk density, volatile matter content, ash content and size distribution are important in selecting the technology and mixing the biomass resources. Ash content in rice husk is 19% (dry mass), whereas it is 5-10% and 0.25-1.7% for diverse agricultural residues and fuel wood respectively (Quaak et al. 1999).

CFB gasifier has been operated successfully in China for gasification of fuel wood and agricultural wastes to generate electricity (Leung et al. 2004). All types of agricultural and forestry wastes can be used for gasification, necessary pre-treatment and cleaning methods of typical CFB gasification based electricity-generation systems are (Leung et al. 2004):

Producer gas cleaner : Dust separator, water scrubber
Feed pre-treatment : Crushing
Operation time (h/yr) : 5000
Lifetime (yrs) : 15

In Bangladesh, district wise availability of agricultural wastes and forestry residues varies widely (see Chapter 5). So, co-gasification of agricultural wastes and forestry residues would be appropriate for decentralised biomass electricity generation. Also, co-gasification would ensure uninterrupted feed supply to the gasifier and generate more electricity in a given district. For gasification-based biomass electricity-generation, biomass resources in Bangladesh have been grouped as follows:

- Group A: Agricultural wastes and Forestry residues
- Group B: MSW (Combustible fraction)
- Group C: Poultry wastes

The national total and district wise availability of these biomass resources were estimated (see Chapter 5).

6.2.5 Capital Investment Cost and Overall Efficiency

Table D1 and Table D2 (in Appendix D) shows the specific investment costs of the gasifier-based electricity generation plants. The components of the capital investment costs of this type of conversion technology are:

- Gasifier, fuel handling system, gas clean up system;
- Engine or turbine (steam or gas turbine);
- Generator and control system;
- Land procurement, civil works;
- Installation, commissioning and training;

Capital investment costs vary depending on whether the plant is only for electricity generation or for CHP production. All the investment costs were converted into US$, in September 2004 value (see Section 6.1). There is also a large difference in capital investment costs between gasifier power plants manufactured in developed countries and plants manufactured in developing countries. For example, in Indonesia, a 30 kW_e imported wood gasifier plant is estimated at US$ 61,800 (US$ 2060/kW_e); whereas a locally manufactured plant is estimated at US$ 31,380 (US$ 1046/kW_e) (Stassen, 1995).

Table D2, in Appendix D, shows the investment costs of the gasifier-based electricity generation plants manufactured in India. Freight, installation, training and commissioning costs need to be added with this to get the total capital investment cost. Stassen (1995) reported the value of US$ 196/kW_e and US$ 126/kW_e (in 1990 value) as freight and installation costs for 30 kW_e and 100 kW_e sized dual-fuelled generator plant respectively. This indicates that as the capacity of the plant increases, per unit cost of the freight and installation decreases. No correlation was found to estimate the freight and installation cost for varying plant sizes. Assuming a little variation for a range of 150-500 kW_e dual-fuelled plants, an average fixed value of US$ 100/kW_e has been used in this study as freight and installation cost (see Table D2, in Appendix D).

The training cost is not directly related to the number of total operators of the plant. The common practice is that the supplier (or manufacturer) arranges training of fixed number of operators, and this cost is included in the total cost of training and commissioning. Training and commissioning cost varies according to the range of plant capacity. In this study, it is assumed that this cost is constant for small- to medium-scale plant range. Stassen (1995) estimated a fixed value of US$ 2000 (in 1990) as training and commissioning cost for small- to medium-scale dual-fuelled (producer gas and diesel) generator plant. A similar cost figure, which is equivalent to US$ 2890 in September 2004, has been used in this study (see Table D2, in Appendix D) to cover training and commissioning cost of the plant.

The major factors which affect the capital investment cost and electrical efficiency of the gasification-based electricity-generating plants are: types of conversion equipment, types of biomass fuel and plant electricity-generating capacity (see Table D1 and Table D2, in Appendix D). Correlations between the specific capital investment costs and plant electricity-generating capacity; and between the electrical efficiency and plant electricity-generating capacity; were developed for gasification-based spark-ignition engine-generator systems (see Figure 6.8 and Figure 6.9) using the data presented in Table D1 and Table D2 (in Appendix D). The fuels used in these types of plants are either agriculture wastes or forestry residues alone or mixture of agricultural wastes and forestry residues. Similar correlations were also developed for gasification-based compression-ignition engine-generator systems (see Figure 6.10 and Figure 6.11). Trends have been generated using the data of both developed and developing countries. The best fit equations for the capital investment cost and for the overall electrical efficiency are:

$$SCI_{\text{spark ignition gasification plant}} = 4388.3(P)^{-0.3529} \tag{6.1}$$

$$\eta_{\text{spark ignition gasification plant}} = 0.3319[\ln(P)] + 14.981 \tag{6.2}$$

$$SCI_{\text{compression ignition gasification plant}} = 4592.1(P)^{-0.4035} \tag{6.3}$$

$$\eta_{\text{compression ignition gasification plant}} = 1.9077[\ln(P)] + 10.459 \tag{6.4}$$

Adequate data of specific capital investment cost and electrical efficiency for MSW and poultry litter gasification-based electricity-generating plants were not found to develop the correlation. In this study, correlations developed for the specific capital investment cost of the gasification-based spark-ignition engine-generator and gasification-based compression-ignition engine-generator plants using agricultural waste and forestry residues, would be used for plants using the MSW and poultry litter as fuel.

The mean electrical efficiency of the data used to generate the electricity efficiency trend lines for gasification-based spark-ignition engine-generator and gasification-based compression-ignition engine-generator plants, using agricultural wastes and forestry residues, are 16.65% and 16.34%, respectively.

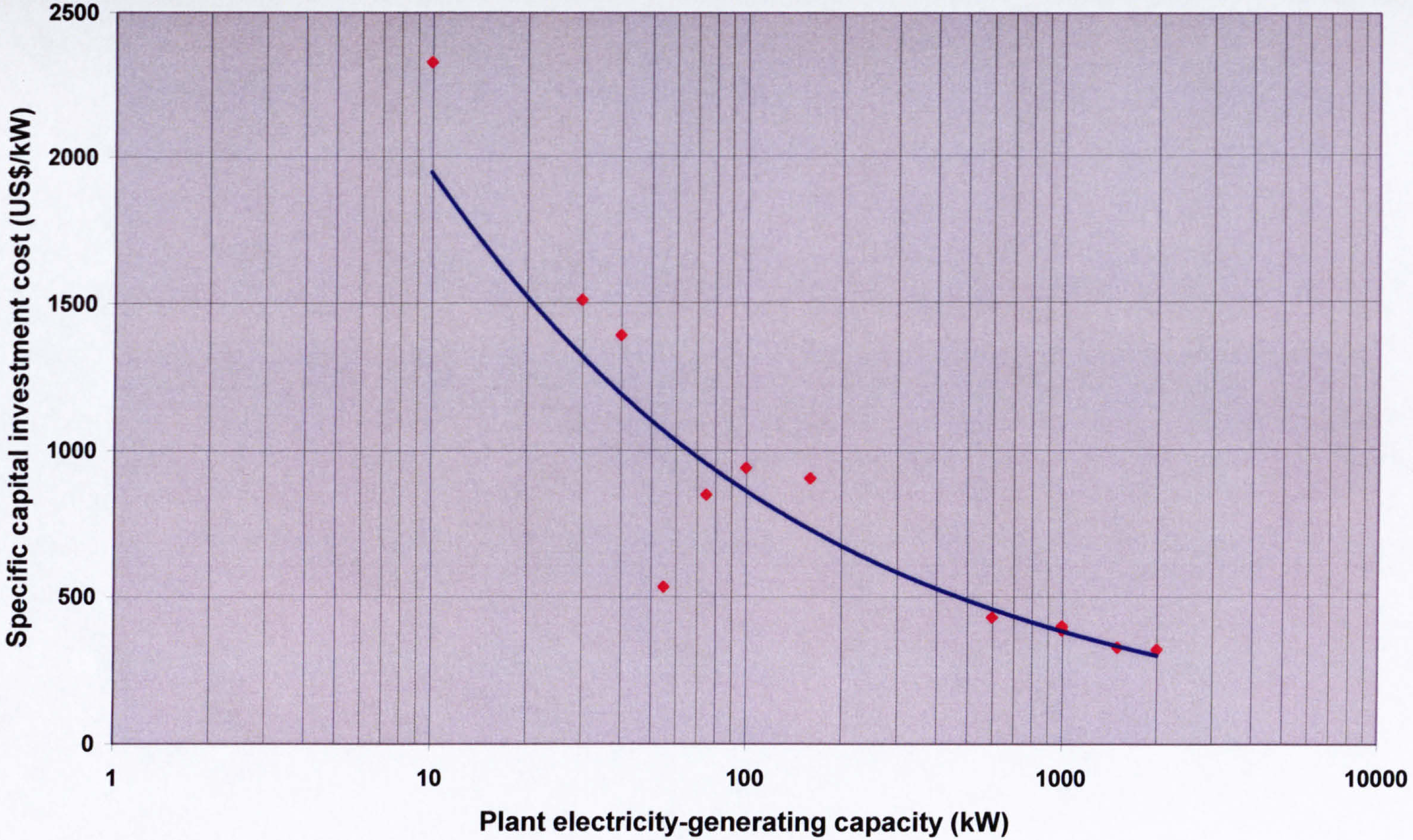


Figure 6.8 Specific capital investment cost of the biomass gasification-based spark-ignition engine-generator plant

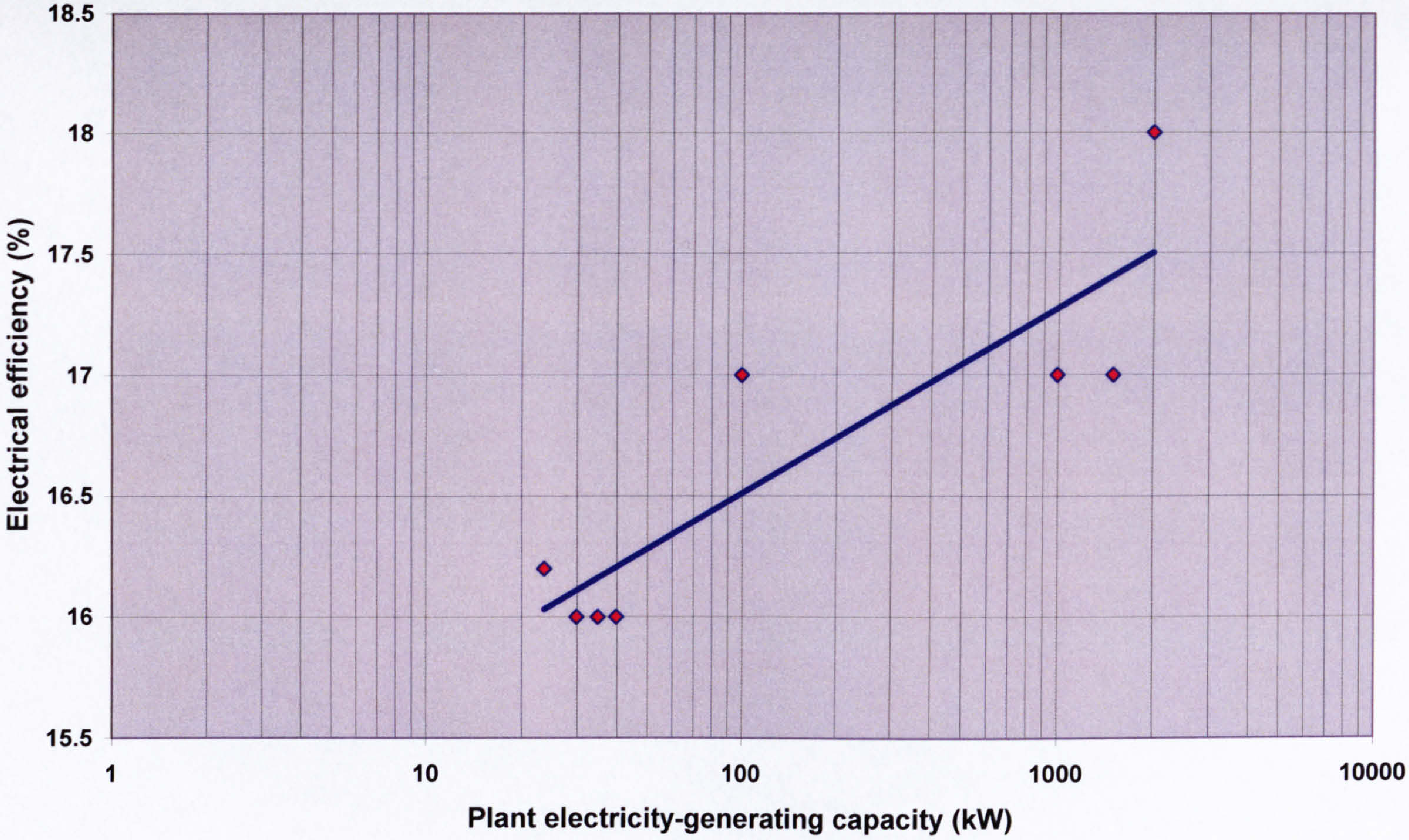


Figure 6.9 Overall electrical efficiency of the biomass gasification-based spark-ignition engine-generator plant

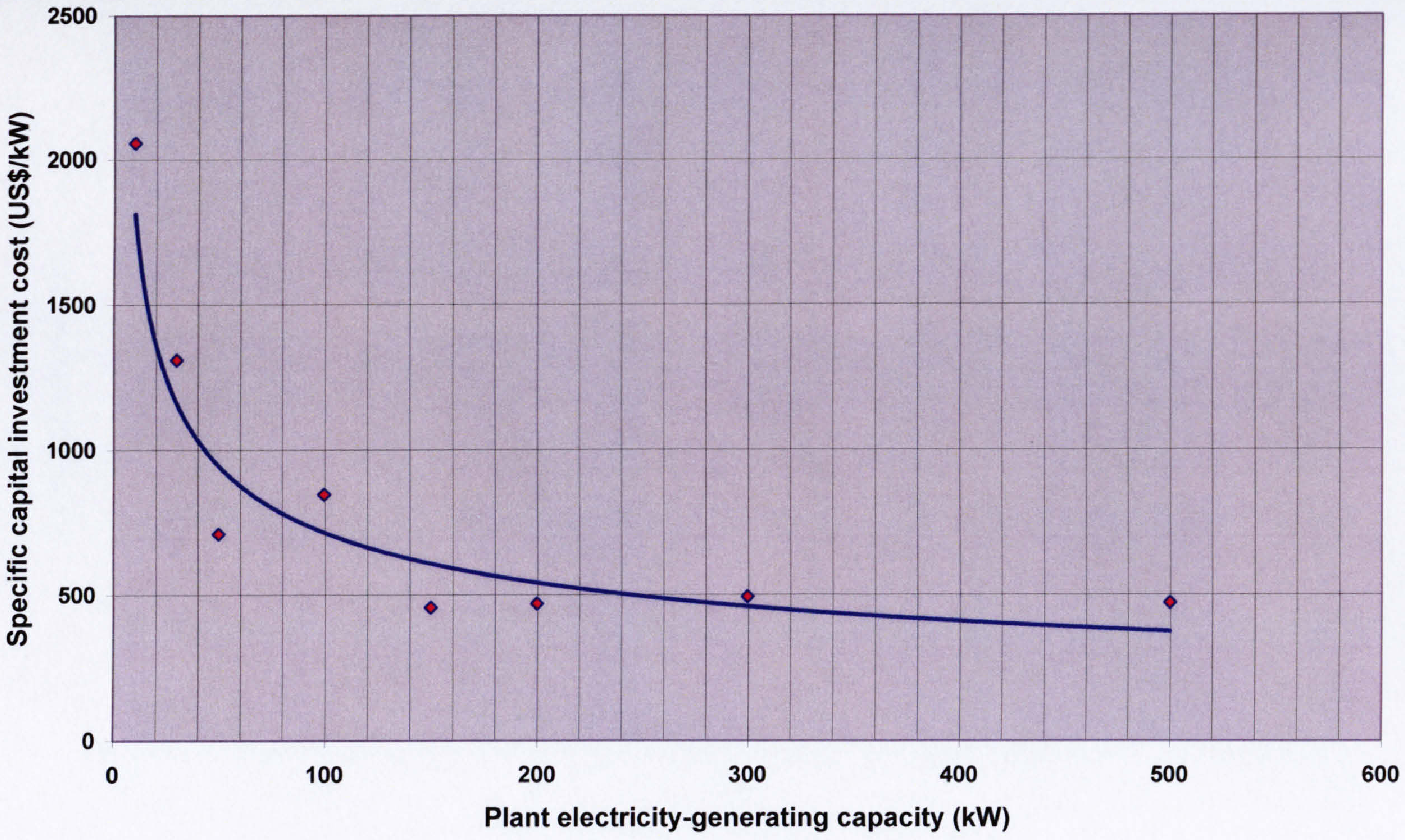


Figure 6.10 Specific capital investment cost of the biomass gasification-based compression-ignition engine-generator plant

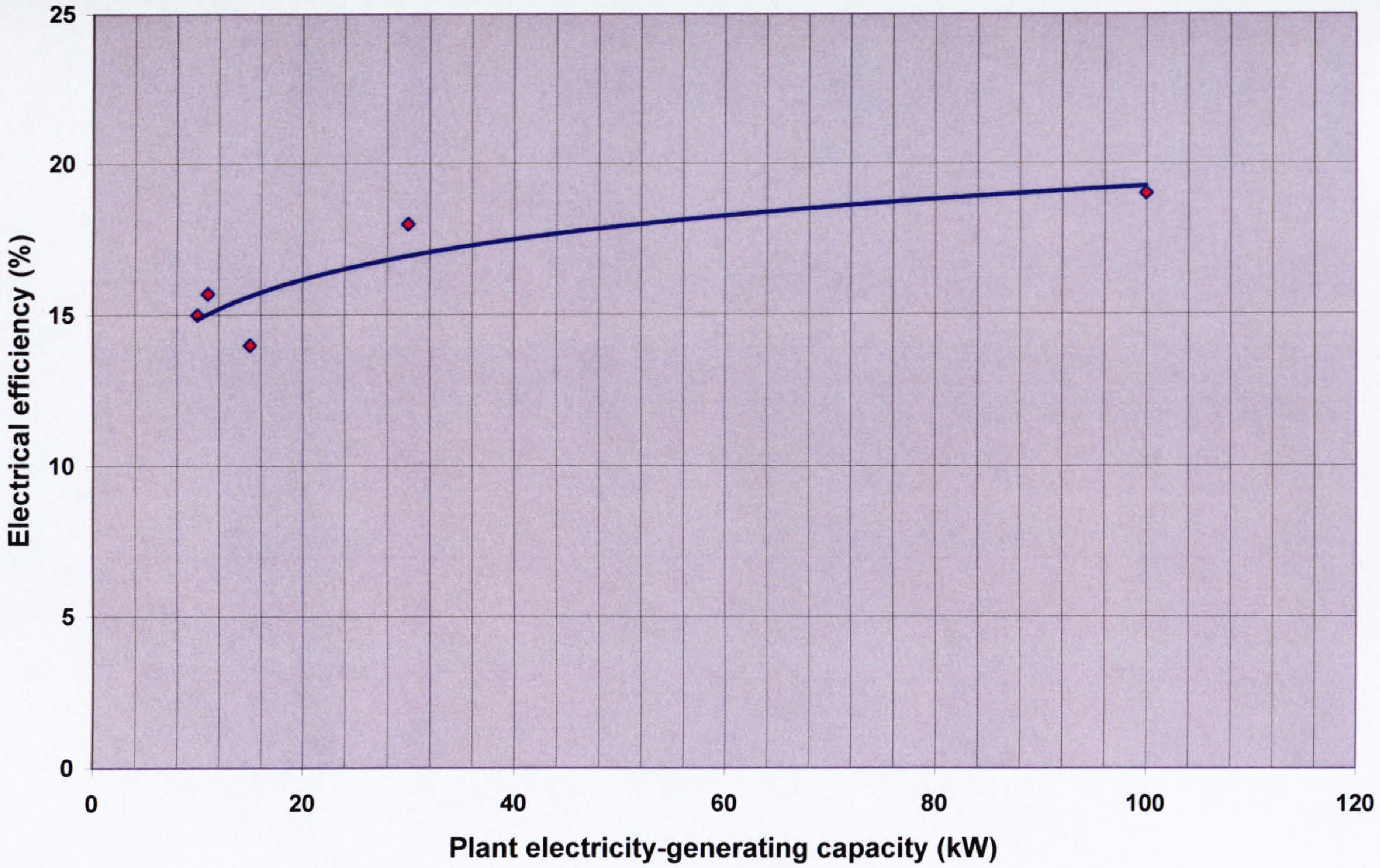


Figure 6.11 Overall electrical efficiency of the biomass gasification-based compression-ignition engine-generator plant

6.3 Anaerobic Digestion

6.3.1 Biomass Resources for Anaerobic Digestion

The biomass resources suitable for the anaerobic digestion in Bangladesh are:

- Animal wastes and poultry droppings
- Organic fraction of the MSW
- Sewage sludge
- Rice and wheat straw

6.3.1.1 Animal and Poultry Wastes

Animal and poultry wastes are widely used for anaerobic digestion both in developing countries and developed countries. The important factors for the utilisation of these wastes, as digester feeds, are:

- Availability of animal waste consistently all year round. The generation of animal waste is variable, depending on the climate and type of feed. This issue was discussed in Chapter 5 of this study.
- Animal waste should be free from larger amounts of bedding and other materials (e.g. sand, stones, and straw). These materials can clog the influent and effluent pipes of the digester and destabilise the biogas production process (EPA, 2002a).
- Daily animal waste collection is desirable because of preserving the biogas production potential and conserving the nutrient value. Generally animal waste is collected at a common point. This point might be a pit, tank or pond. Digester is fed from this common point. Necessary preparations (e.g. adding water, mixing and separating from solids) of waste are made before feeding into the digester. Digester feeding should be in regular intervals; irregular feeding can disrupt the biological process and cause the process to operate inefficiently or to stop entirely (EPA, 2002a).

6.3.1.2 Municipal Solid Waste

Organic fractions of the MSW from household and municipal authorities provide potential feedstock for anaerobic digestion. Both the composition and definition of MSW varies from one country to another depending upon standard of living, cultural practices, and extent of recycling. MSW is heterogeneous material that contains a wide range of components but these can be grouped into three broad fractions:

- Organic fraction – is the readily biodegradable organic matter such as kitchen waste, food residues, paper and cardboard, grass cuttings, tree clippings, and other garden wastes.
- Combustible fraction – includes slowly biodegradable and stable organic matter such as coarse wood, plastics and other synthetic materials.
- Inert fraction – typically includes stones, sand, glass and metals. Some of these products are suitable for recycling; the remainder can be land-filled.

RISE-AT (1998) reported that 30-60% by mass of MSW is organic matter. In general, about 50% (by mass) of MSW is organic matter (Braber, 1995). The organic fraction of MSW, in Bangladesh, is around 50-55% (see Table 6.7). The main steps in the treatment of MSW by anaerobic digestion (AD) are:

- Separation: organic fraction of the MSW is separated. Mechanical separation techniques are used if the separation is not performed at the source of MSW (RISE-AT, 1998).
- Anaerobic digestions. AD produces biogas for energy and partially deodorizes, stabilize and disinfect the digestate.
- Post treatment. This completes the stabilization and disinfection of the digestate, removes residual contaminants, and produces a refined product. In the case of co-digestion of MSW and sewage sludge, the viruses and bacteria can remain in the digestate after the anaerobic digestion process. Waste treatment at 70°C is recommended either before or after the digestion process (RISE-AT, 1998).

6.3.1.3 Sewage Sludge

The digestion of sewage sludge provides sanitation, reduces the odour potential from the sludge and produces energy. It is usually delivered in liquid form at approximately 5% TS or dried to 20-25% TS (IWM, 1998). The addition of 5% by mass sewage sludge to MSW has been proved to give good process performance and reactor stability, but better performance of anaerobic digestion can be achieved with a feedstock of 80/20 ratio (by mass) of MSW and sewage sludge (IWM, 1998).

6.3.1.4 Rice and Wheat Straw

The anaerobic digestion is possible for feed stocks with carbon-to-nitrogen (C/N) ratio of up to 45/1 (IWM, 1998). C/N ratios of the rice straw and wheat straw are 67 and 87 respectively (LGED, 2004). If the C/N ratio is very high, gas production will be low, because the nitrogen will be consumed rapidly by methanogens process for meeting protein requirements. So, the retention time for straw digestion is quite high. By mixing straw with other biomass resources of low C/N ratio would produce a reasonable C/N ratio.

Composition	Fraction by mass (%)
Paper	10.0
Glass	1.4
Metal	0.5
Plastic	2.6
Textile	2.5
Wood, Grass	22.0
Ash, Soil	40.0
Food waste	18.0
Others	3.0
Total	100

Table 6.7 Physical composition of MSW at Dhaka, Bangladesh (REIN, 2005e)

6.3.2 Technology

Biogas-based electricity generation system consists of the following components/subsystems (see Figure 6.12):

- Biomass collection and transportation
- Digester
- Effluent storage
- Biogas handling (piping and storage)
- Biogas conversion equipment
- Generator and control system

Over 1.85 million animal waste digesters were installed in India by the mid 1990s, about one third of these were not operating in early 2000 for a variety of reasons, but mainly due to availability of feed material and delivery difficulties. In China, about 5 million family biogas plants were in operation in mid 1990s. In addition to these, there were 500 large scale digester operating at large pig farms and other sites, and some other 24,000 digesters operating at urban sewage treatment plants. There are several thousands biogas plants operating in other developing countries, most notably in South Korea, Brazil, Thailand, and Nepal (Kartha and Larson, 2000). In developed countries, most industrial and municipal digesters are mainly used for the environmental benefits they provide. An estimated 5000 digesters are installed in developed countries, primarily at large livestock processing facilities and municipal sewage treatment plants (Kartha and Larson, 2000).

6.3.2.1 Types of Digester

The basic important requirement of a digester is that it should be air and water tight. Based on feeding the biomass, the digesters are of two types: Batch digester and Continuous fed digester.

A batch digester operates on a single charge until it is exhausted. At the end of the digestion process, the digester is emptied and reloaded for a new cycle. For this type, more than one digester is needed to guarantee the continuous supply of biogas. In a continuous fed digester, the feed material and digested slurry are added and removed at regular intervals. This type is less expensive, but requires close monitoring of feedstock solids. Commonly used continuous fed biogas digesters are (LGED, 2004; Kartha and Larson, 2000; and SDdimensions, 1997):

(i) Floating-cover type digester: This type of was introduced commercially in India by the Khadi and Village Industries Commission (KVIC). The reactor walls are brick or concrete and the reactor is covered with a floating steel cylinder (see Figure 6.13). As the cylinder has a constant weight, it moves up when gas production is higher than consumption and vice versa.

(ii) Fixed-dome type digester: Fixed dome Chinese model biogas plant was built in China as early as 1936. It consists of an underground brick masonry compartment (fermentation chamber) with a dome on the top for gas storage (see Figure 6.13). Due to corrosion of the steel dome in floating type digester, the gas leakage problem happened. Fixed dome type design has become popular to avoid this problem.

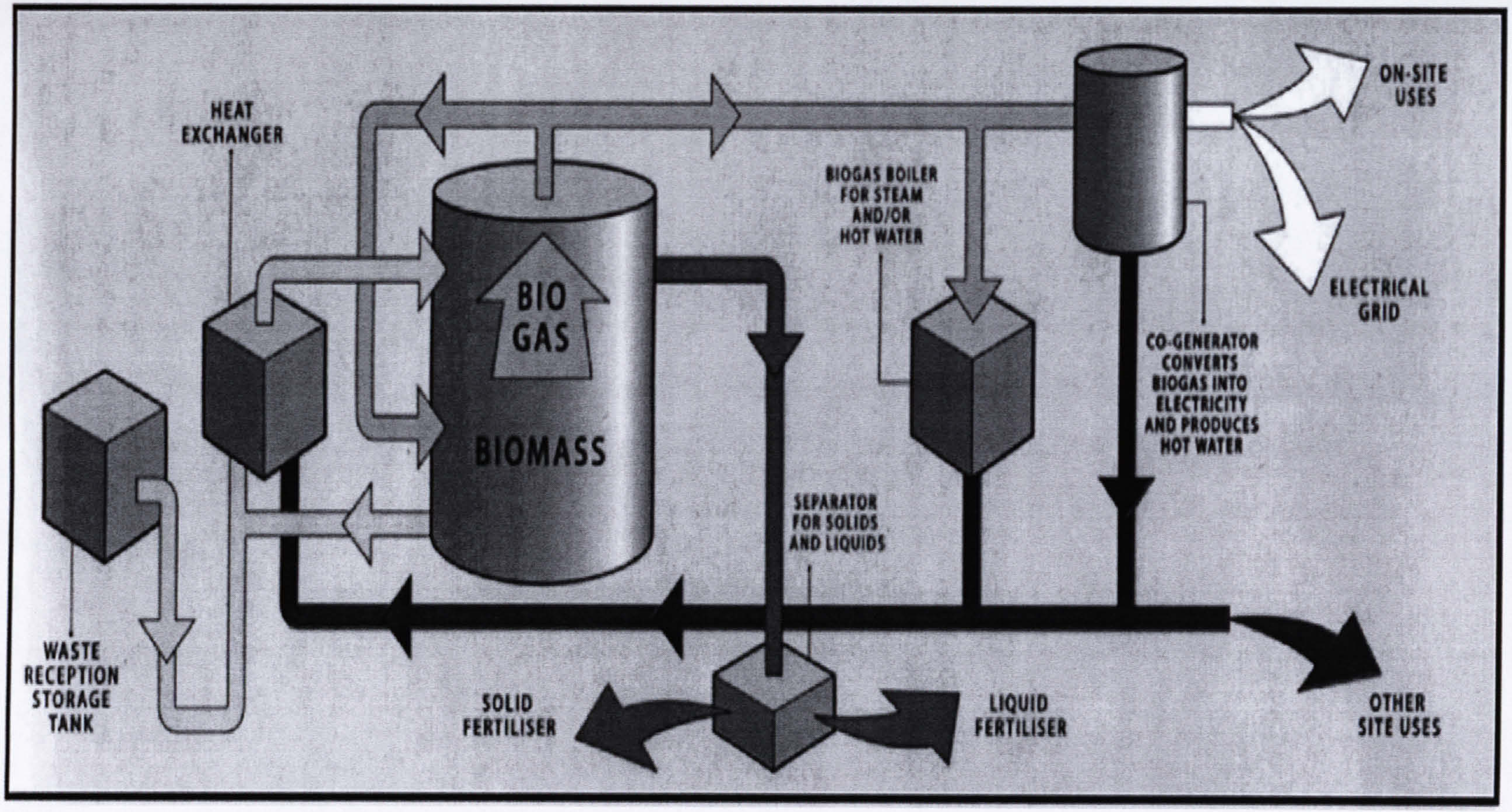
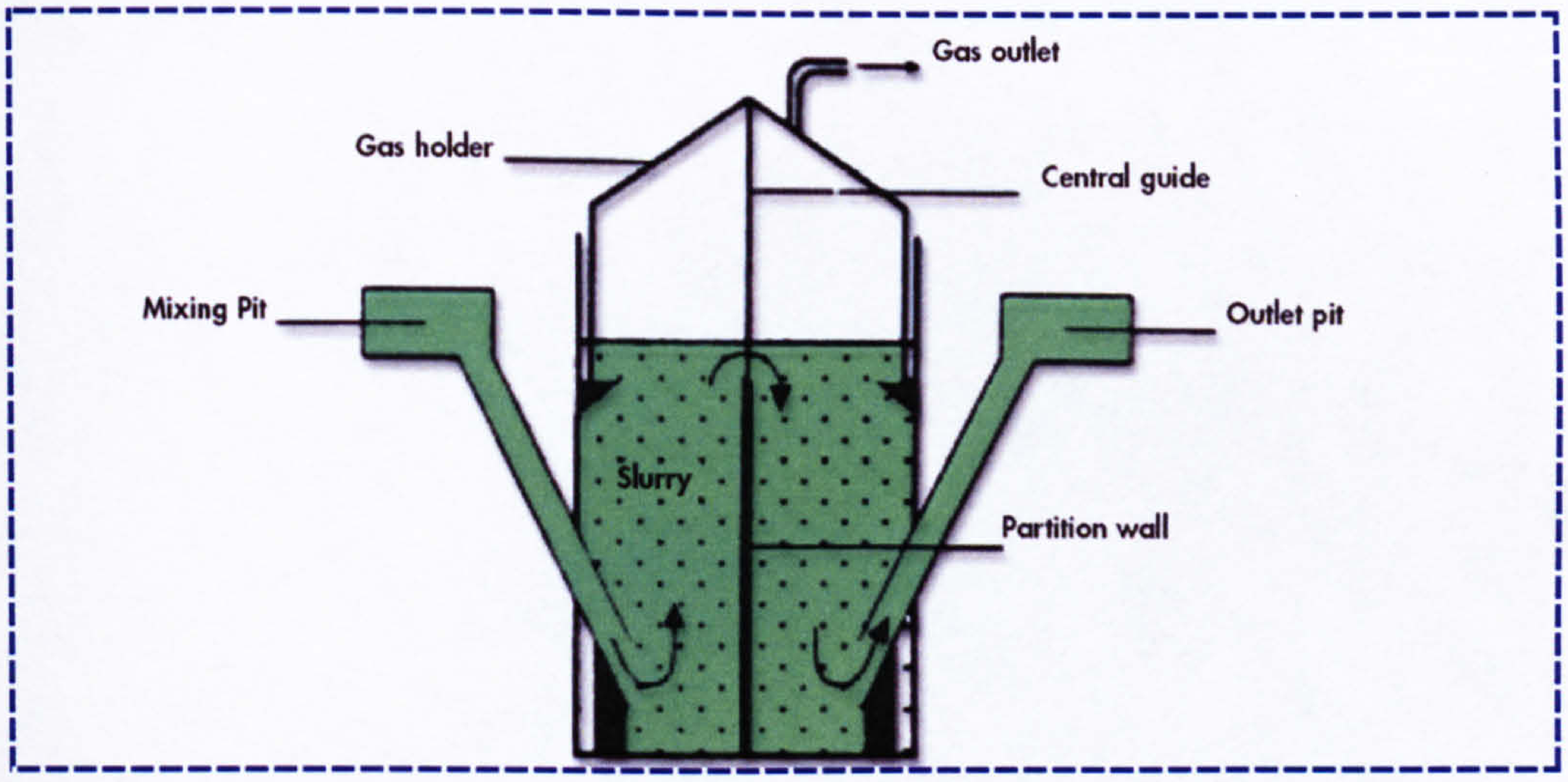


Figure 6.12 Anaerobic digestion systems (Smith, 2002)

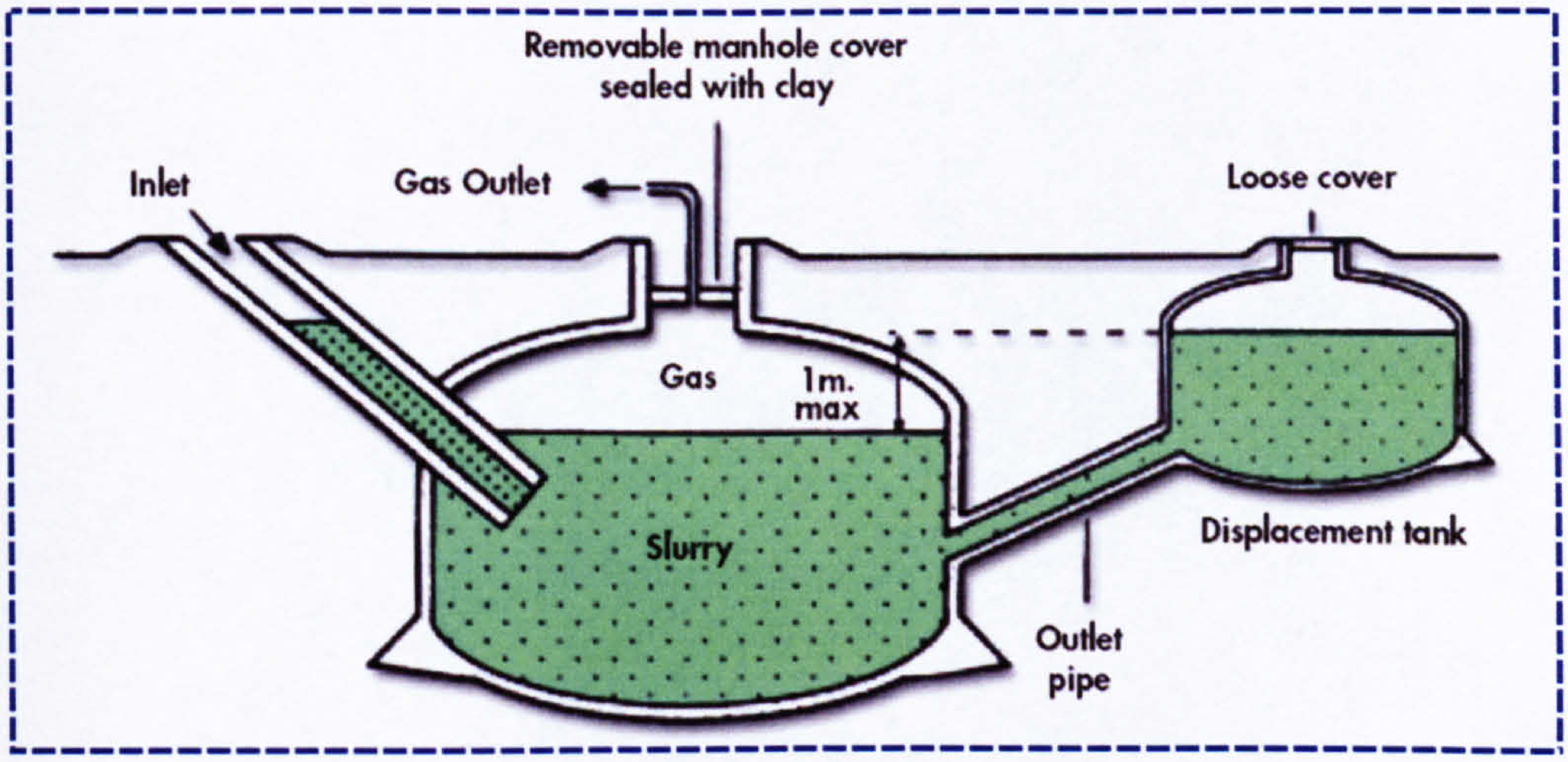
Pressure inside the digester rises, when the rate of gas production is higher than that of gas consumption. In this case, the system expels some digester contents into the outlet compartment. In the opposite situation, when the consumption is higher than production, pressure inside the digester falls and the expelled materials in the outlet compartment run back to the digester.

(iii) Bag digester: This type of digester was first developed in the 1960s, in Taiwan. It consists of a long cylinder made of PVC. Bag type digester was developed to solve the problems experienced with brick and metal digesters.

(iv) Plug flow digester: This type of digester is similar to the bag digester. It consists of a trench lined with concrete or an impermeable membrane. The reactor is covered with either a flexible cover gas holder anchored to the ground or galvanized iron top. This type of design was first used in South Africa in 1957.



(a) Floating-cover digester



(b) Fixed-dome

Figure 6.13 Schematic diagram of commonly used biogas digester used in India and China (Kartha and Larson, 2000)

(v) Anaerobic filter: This type of digester was developed in the 1950's to use relatively dilute and soluble waste water with low level of suspended solids. It consists of a column filled with a packing medium. A great variety of non-biodegradable materials such as stones, plastic, coral, mussel shells, reeds, and bamboo rings were used as packing media. The methane forming bacteria form a film on the large surface of the packing medium and are not carried out of the digester with the effluent.

(vi) Up flow anaerobic sludge blanket (UASB): This type of digester was developed in 1980, in the Netherlands. It is similar to the anaerobic filter type, in that it involves a high concentration of immobilized bacteria in the reactor. However, the UASB reactors contain no packing medium; instead, the methane forming bacteria are concentrated in the dense granules of sludge blanket which covers the lower part of the reactor. The feed liquid enters from the bottom of the reactor and biogas is produced while liquid flows up through the sludge blanket. Many full-scale UASB plants are in operation in Europe using waste water from sugar beet processing and other dilute wastes that contain mainly soluble carbohydrates.

6.3.2.2 Prime movers

Engines and micro gas turbines electricity generator sets are used to generate electricity by utilising the biogas as a fuel. Engines are of two types: internal combustion engines (ICEs), and external combustion engines.

6.3.2.2.1 Internal Combustion Engines

The most commonly used prime mover for biogas-based electricity generation is ICE. Types of ICEs are:

Spark Ignition Engine: The octane number of gasoline and methane is 86 and 130 respectively (Barker, 2001). Methane is the major component of biogas, which makes it a suitable fuel for spark ignition engine. In terms of energy equivalents, 1.33-1.87 m^3, and 1.5-2.1 m^3 of biogas are equivalent to one litre of gasoline and diesel fuel, respectively (Marchaim, 1992). Electrical efficiency of this type of engine is around 25% at full load, falling off at part load (Picken, 1989). Manufacturers of bigger gas engine-generator set (>0.5 MW_e) offering the conversion efficiency of 35 - 40% of the input energy, which is very promising for biogas-based electricity-generating plants. (Tafdrup, 1995).

Compression Ignition Engine: In this type, certain percentage of diesel fuel needs to be injected for efficient combustion of biogas. Picken (1989) reported that a minimum of 7% by volume of the total fuel needs to be supplied as diesel oil. Electrical efficiency of this type of engine-generator set is 30 - 35% throughout the load range (Picken, 1989). This type of engine is very desirable when biogas production fluctuates. If the production of biogas is low, then the amount of diesel is increased and maintains the electricity generation. In case of malfunctioning of the digester or lack of biomass fuel supply, an immediate change to full diesel operation is possible.

6.3.2.2.2 External Combustion Engines

Types of external combustion engines are:

Stirling Engine: In Stirling engine, combustion of the fuel takes place in an external boiler or furnace. Mechanical work is derived from the pressure changes that result from the cyclic heating and cooling action of the enclosed working gas. Solid, liquid or gaseous (i.e. biogas) fuels derived from biomass can be used as a fuel. The advantages of Stirling engine are: high efficiency, which is up to 40%; and very low noise, being only about 10-20% of the level produced by an ICE with the same capacity (Lin et al. 1998).

Steam Engine: Steam engine-generator systems can generate electricity from 20 kW upwards (Lensu and Alakangas, 2004). For >1 MW_e capacity, steam turbines are used instead of steam engine due to its higher investment costs (for massive construction) (Lensu and Alakangas, 2004). The advantages of steam engines are: high reliability, low maintenance and simple control. Steam engines are not popular for biomass-based electricity generation due to its high capital investment cost and relatively low conversion efficiency.

6.3.2.3 Accessories and Control Systems

The equipments used for biogas handling are: piping, valves, gas meters, pressure regulators, and gas scrubbers. Gas scrubbers are needed to remove the corrosive compounds (mainly H_2S) present in the biogas. Scrubbing of CO_2 from biogas is possible by methanation process, which is costly (Bari, 1996). Biogas containing more than 40% CO_2 needs scrubbing as it starts deteriorating the ICEs performance, provision should be made to flow adequate biogas for high CO_2 content (Bari, 1996).

The employment of reconditioned car engines could be a promising option to reduce the capital investment cost of the plant. Such spark ignition type engines need little modifications to use with biogas. The important modification is the replacement of the carburettor with a gas-air mixer with throttle valve to control biogas-air mixture for getting the better engine performance. However, in general, the electrical efficiency of the plant would drop with the use of a reconditioned car engine. There is a decrease in efficiency of 15-20%, when a spark ignition carburetted engine is converted to natural gas engine. This is due to the decrease in volumetric efficiency (because of gaseous fuel) and lower flame speed of air-gas mixture compared with air-gasoline mixture (Henham and Makkar, 1998). For utilising reconditioned car compression ignition engines as dual-fuelled engines for biogas application, the modification of the engine is almost similar. Air and biogas mixes in a mixing chamber and then ignited by energy from the combustion of the sprayed diesel fuel.

Control systems are simple and readily available. Such systems are employed for protecting the engine and the electrical load by shutting the engine off, either in the case of any serious engine faults (e.g. high temperature, low level of oil/water, low biogas supply) or if the load is switched off. Moreover, control system shuts the engine off, if the load is too high or if the electricity generated is outside the specified voltage and frequency ranges.

6.3.2.4 Temperature of Digestion

Maintaining the digester temperature at the level desired is very important. The usual value of digester temperature is 35^0 C (Hall, 1989). In Bangladesh, the average ambient temperature during most of the year, is 30~35^0C, which is favourable for anaerobic digestion to occur. However, in winter periods, some form of heating is needed to maintain the digester temperature. The most common methods of maintaining the digester at an elevated temperature are:

- Using some percentage of the biogas generated.
- Utilising the exhaust gas from engine, through a heat exchanger.
- Using a water-cooled engine instead of an air-cooled engine.

6.3.2.5 Use of Digester Effluent

The uses of the digester effluent are:

- As fertilizer. The digester effluent is usually dried in the sun, either separately or in combination with agricultural wastes before using it as a fertiliser (Marchaim, 1992). The organic components of the digester effluents are rich in nitrogen, phosphorus, potassium, and nutrients. Storage facilities are required to store the effluent.
- Aquaculture. The digester effluent can be used to stimulate the growth of algae in fishponds and thereby provide feed for fish.
- In mushroom production. In general, digester effluent is free from bacteria and pathogens and is a very good media for cultivation of mushroom. It has been reported that the mushroom production increased by 30%, as a result of using the digester effluent instead of normal cultivation practises (Henderson, 2004).
- Seeds fermentation. Digester effluent also used for seeds fermentation. It has been proven that soaking seeds in digester effluent for 12 hours prior to germination rather than soaking in water increases corn sproutability from 92.5% to 95%, and increases early growth in the plants by 5% (Henderson, 2004).

6.3.3 Biogas Production: Important Parameters

The biogas produced is actually a mixture of mainly methane and carbon dioxide. Methane is a combustible gas. The energy content of biogas depends on the amount of methane it contains. Typical biogas composition and heating value reported by RISC-AT (1998) are:

Methane (by vol.) : 55 - 70 %
Carbon dioxide (by vol.) : 30 - 45% by vol.
Hydrogen Sulphide (ppm by vol.) : 200 - 4000
Energy content (MJ/m^3) : 20 - 25

Factors, which effect AD processes, are:

Nutrients and Organic Fraction: Nitrogen is the main nutrient for the growth of methane forming bacteria. The necessary nutrients in the descending order of importance are nitrogen, sulphur, phosphorous, iron, cobalt, nickel, molybdenum, selenium, riboflavin, and vitamin B12 (IWM, 1998). C/N ratio between 20 and 30 is favourable for biogas production (Sϕrensen, 2000).

Moisture Content: Moisture content of feedstock is an important parameter. Water provides the medium for chemical reactions, transport nutrients and allow the micro organisms to move from place to place. If moisture content is high, larger reactor volume required (IWM, 1998). Reliable anaerobic digestion has been reported at digestate TS levels up to 50% (IWM, 1998). The ideal value of TS content is 5-20% (Hall, 1989).

Retention Time: Retention time depends on the ease of biodegradation, the concentration of biomass present and the contact time. On the other hand, the rate of degradation depends on the temperature of the process and the predominance of bacterial species. The range of retention time for single stage, mesophilic anaerobic digestion of MSW is 12-25 days (IWM, 1998).

pH: Ideal pH range for AD process should be in between 6.4 and 7.2 (IWM, 1998). If the C/N ratio is very low, nitrogen will be liberated and accumulated in the form of NH_4. NH_4 will increase the pH value of the content in the digester. A pH value higher than 8.5, will start showing toxic effect on methanogen population (SDdimensions, 1997). Low pH can also inhibit acidogenic conversion of the substrate (IWM, 1998).

Reactor Mixing: Mixing improves the contact between micro-organisms and substrate and influences the ability of the bacteria to obtain nutrients. Also, mixing improves heat transfer and contributes to the maintenance of uniform temperature throughout the reactor. Mixing has little effect on the biogas production rate or quality but a great effect on the quality of the digestate and the working volume of the reactor (IWM, 1998).

Oxygen Sensitivity: AD process proceeds in the absence of oxygen. 5-15% by volume of methane in air is explosive (IWM, 1998), so care must be taken to avoid the dangerous mixtures of oxygen and biogas to occur in the system.

6.3.4 Co- digestion of Biomass Resources

It has been proven that biogas production could be increased by mixing materials with high C/N ratio with those of low C/N ratio (RISC-AT, 1998). Biogas production rates of animal waste and sewage sludge are 0.380 m^3/kg VS and 0.265 m^3/kg VS respectively, however, a 16% increase in the biogas production rate (i.e. 0.407 m^3/kg VS) is reported if this two biomass resources are co-digested at 50:50 mixing ratio (see Table 6.8). RISC-AT (1998) reported that the joint treatment of MSW with animal manure/sewage sludge is a popular method in existing plants, which tends to be simpler and is economically more viable than an MSW - only treatment system. In China, as a means to balance C/N ratio, it is customary to load rice straw at the bottom of the digester upon which human waste is discharged (SDdimensions, 1997). Similarly, at Machan Wildlife Resort located in Chitawan district of Nepal, feeding the digester with elephant dung in conjunction with human waste enabled to balance C/N ratio for smooth production of biogas (SDdimensions, 1997). Overall merits of co-digestion are (Braun and Wellinger, 2004):

- Improved nutrient balance
- Increased and steady biogas production throughout different seasons
- Increased quantity of digestate to use as a fertilizer

Type of biomass	Operating conditions: temperature (°C)/ retention time (days)	Mixing ratio for co-digestion	C/N ratio	Biogas production (m^3/kg TS)	Reference
Animal waste	35 / 60	-	25	0.300	LGED (2004)
Animal waste	20 - 25 / 60	-	25	0.200–0.250	LGED (2004)
Animal waste	- / 40	-	-	0.380[a]	Shah (1997)
Animal waste	-	-	-	0.360	Nagamani and Ramasamy(1999)
Cow (bull) dung	35 / -	-	-	0.250	Shannon (1996)
Cow dung	-	-	25[b]	0.340	Omer and Fadalla (2003)
Cow dung	30 / 55	-	25	0.300	Devkota (2003)
Cow dung	35/ 55	-	25	0.450	Devkota (2003)
Buffalo waste	-	-	-	0.540	Nagamani and Ramasamy (1999)
Poultry waste	-	-	-	0.480	Omer and Fadalla (2003)
Poultry waste	- / 40	-	-	0.617[a]	Shah (1997)
Poultry (chicken) waste	35 / 32	-	25[b]	0.350–0.400	Shannon (1996)
Sewage sludge	-	-	13[b]	0.400	Omer and Fadalla (2003)
Sewage sludge	- / 40	-	13[b]	0.265[a]	Shah (1997)
Sewage sludge	35 / 60	-	13[b]	0.430	LGED (2004)
Water hyacinth	-	-	-	0.400	Omer and Fadalla (2003)
Water hyacinth	30	-	-	0.160	LGED (2004)
Green grass	-	-	-	0.630	LGED (2004)
Weeds	- / 40	-	-	0.277[a]	Shah (1997)
Wheat straw	35 / 60	-	87	0.450	LGED (2004)
Wheat straw (chopped / ground)	35 / -	-	-	0.400/ 0.550	Shannon (1996)
Vegetable wastes	-	-	-	0.250	IWM (1998)
MSW (30% biodegradable)	-	-	-	0.040	IWM (1998)
Biowastes[d]	-	-	40[e]	0.100–0.200[c]	RISE-AT (1998)
Biowastes[d]	-	-	-	0.100- 0.228[c]	Schmidt and Pinapati (2000)
Biowastes[d]	-	-		0.125	IWM (1998)
Animal waste + Weeds	- / 40	50:50	-	0.363[a] (5)*	Shah (1997)
Poultry waste + Sewage sludge	- / 40	50:50	-	0.413[a] (1)*	Shah (1997)
Animal waste + Poultry waste	- / 40	50:50	-	0.528[a] (6)*	Shah (1997)
Animal waste + Sewage sludge	- / 40	50:50	-	0.407[a] (16)*	Shah (1997)
Sewage sludge + Weeds	- / 40	50:50	-	0.387[a] (39)*	Shah (1997)

*figures between brackets represent the % increase in biogas production due to co-digestion over that for the average of two wastes digested separately.

a biogas rate in m^3 / kg volatile solid (VS)
b C/N data collected from reference source Sϕrensen (2000)
c in m^3 / kg bio waste;
d bio wastes is defined as the organic fraction of MSW
e for whole MSW

Table 6.8 Biogas production rate as a function of the operating conditions and mixing ratio

6.3.5 Potential Biomass Resources

The retention time for wheat straw is 60 days for biogas produced to more than 90% of the total yield, whereas it is 30-40 days in the case of animal waste (LGED, 2004). Due to high retention time, seasonal availability dependence and relatively lower quantity of district wise availability (see Chapter 5), the rice and wheat straw were excluded from the current estimate of biogas production potential in Bangladesh. Based on the advantages of co-digestion presented in section 6.3.4, biomass resources in Bangladesh have been grouped primarily into the following two digestible mixtures:

- Group A: Animal waste and poultry droppings
- Group B: Organic fraction of MSW and sewage sludge

C/N ratio and MC are the two important parameters for designing a recipe for co-digestion. The effect of MC is more critical compared to the effect of C/N ratio, because too high or too low MC tends to stop the digestion process (Cochran and Carney, 1996). If there are limitations on the availability of one of the sources of biomass in the group, the mixing ratio is determined based on the availability of the biomass resource in short supply. District wise poultry droppings availability in Bangladesh, is not enough (see Chapter 5) to digest it alone. The ratio of animal waste to poultry waste availability in the whole of the country is 31:1 (see Chapter 5). The C/N ratio of the animal waste, and poultry wastes are 25, and 18 respectively (LGED, 2004; Sørensen, 2000). Assuming the mixing ratio is equal to the availability ratio (i.e. 31:1) and using the individual C/N ratio; the C/N ratio of group A mixture is estimated at 25, which is favourable for the production of biogas.

If the MC and amount of dry mass of a biomass resource is known, then the wet mass of biomass can be estimated as:

Quantity of wet mass = [Quantity of dry mass / (1 – MC)]

MC of poultry dropping varies, assuming an average MC of 50% for mixed type (boiler and layer) of poultry droppings; and MC of 83% for animal waste (see Table 6.9); the wet mass of the animal waste and poultry droppings for mixing ratio of 31:1 are 182 kg and 2 kg, respectively. Based on this estimation, the overall MC of group A mixture becomes 84.3%.

The biomass availability ratio of sewage sludge and the organic fraction of MSW is 1.6:1 (see Chapter 5). The C/N ratios of sewage sludge and MSW are 13 and 40 respectively (RISE-AT, 1998; and Sørensen, 2000). So, based on the individual C/N ratio and mixing ratio of 1.6:1, the C/N ratio of group B biomass mixture becomes 23; which is favourable for biogas production. Using the moisture content reported in Table 6.9, the wet mass of the sewage sludge and MSW, for mixing ratio of 1.6:1; are 8 kg and 1.8 kg, respectively. The overall MC for co-digestion becomes 73.6%.

The amount of water needed for maintaining specific moisture content of the mixed recipe can be calculated as:

$$W_w = W_f - W_i = \frac{W_m}{(1-MC_f)} - \frac{W_m}{(1-MC_i)} = \frac{W_m * (MC_f - MC_i)}{(1-MC_f)*(1-MC_i)} \qquad (6.5)$$

Biomass resources	Nitrogen content		Moisture content	
	(% dry mass)	Reference	(% by mass)	Reference
Poultry wastes:		(Cochran and Carney, 1996)		(Cochran and Carney, 1996)
Broiler	1.6 -3.9		22-46	
Layer	4-10		62-75	
Animal wastes	0.29	LGED (2004)	83	LGED (2004)
MSW	1.2	RWEDP (2002a)	45	REIN (2005e)
Sewage sludge	2.96	RWEDP (2002a)	80	LGED (2004)

Table 6.9 Moisture content of biomass resources suitable for AD in Bangladesh

where

W_i	Wet mass of initial mixture
W_m	Dry mass of the mixture (TS)
W_f	Wet mass of the final mixture for the desired moisture content
W_w	Mass of water to be added for the desired moisture content
MC_f	Desired or final moisture content
MC_i	Moisture content of the initial mixture

Bangladesh has many rivers, canals, and ponds. So, there is a big potential of the aquatic biomass (i.e. water hyacinth) in the country. No estimation is available of the availability of this biomass resource. But, a reasonable quantity could be used for anaerobic digestion. The C/N ratio of the water hyacinth is 25 (SDdimensions, 1997). So, mixing water hyacinth with either group will keep the overall C/N ratio of the mixture in the optimal range.

Adequate experimental results of biogas production rates for different types of co-digestion mixtures (with various mixing ratio) are not available in the literature. Biogas production rates have been estimated as:

Group A: C/N ratio of the group A mixture is almost the same as the C/N ratio of the animal waste (i.e. 25). So, biogas production rate of the animal waste alone, i.e. 0.300 m^3/ kg TS (LGED, 2004), could be considered as the biogas production potential of the group A biomass mixture.

Group B: The biogas production rates of sewage sludge and bio-wastes are 0.430 and 0.125 m^3/kg of TS respectively (see Table 6.8). Based on the mixing ratio (i.e. 1.6:1), and individual biogas production rates, the biogas production rate of the mixture is estimated at 0.313 m^3/kg TS.

As a conservative figure, the LHV of the biogas produced from either group of co-digestion mixtures were assumed to be 20 MJ/m^3 (see section 6.3.3).

6.3.6 Capital Investment Cost and Overall Efficiency

The components of the capital investment costs of a biogas-based electricity generation system are the costs of:

- the digester and biogas cleaning system;
- engine or gas turbine;
- generator and control system;
- optional heat recovery system;
- land procurement and civil works;
- installation, commissioning and training;

Investment costs data reported in Table D3 and Table D4 (in Appendix D), were converted into US$, in September 2004 value (see Section 6.1). Biogas digesters built in the developing countries are either family or community scale (see Table D4, Appendix D). The specific capital investment widely varies depending on the scale and the technology employed. For the individual household scale, fixed dome digesters are 40 to 50% less capital intensive than floating-cover digesters (Karha and Larson, 2000).

Digester is a major component of the biogas plant and commonly constructed locally with locally available materials using local labour. So, there are significance variations in specific capital investment costs (US\$/kW$_e$) of the biogas-based electricity-generating plants (see Table D3, in Appendix D). Some of the plants are used for CHP application. The capital investment cost of a CHP plant is higher than the corresponding costs for only an electricity-generating plant (see Table D3, Appendix D). From the review of the data presented, it can be concluded that the variation of the specific capital investment costs (US\$/kW$_e$) are related to the following factors:

- electricity-generating capacity of the plant;
- whether the plant is manufactured locally or imported;
- types of conversion equipment;
- whether the plant is for electricity generation or for CHP application;

Factors which affect the electrical efficiency are (see Table D3, Appendix D):

- electricity-generating capacity of the plant;
- types of conversion equipment;
- types of biomass (methane content varies as biomass varies);

Data for plants (see Table D3, in Appendix D), for only electricity generation were employed to generate the trend line. Correlations between the specific capital investment costs and plant electricity-generating capacity; and between the overall electrical efficiency and plant electricity-generating capacity were developed for biogas-based spark-ignition engine-generator plants (see Figure 6.14 and Figure 6.15). The variation in biogas quality due to different types of biomass feedstock's was assumed negligible. Due to lack of enough data, for plants in the developing countries; data for plants in developed countries (i.e. Europe and the USA) were used to develop the correlations (see section 6.1). The resulting equations for the specific capital investment cost and for the overall electrical efficiency are:

$$SCI_{\text{biogas plant}} = 14317(P)^{-0.2706} \tag{6.6}$$

$$\eta_{\text{biogas plant}} = 20.103(P)^{0.0862} \tag{6.7}$$

Adequate data are not available to develop the investment cost and efficiency correlations for biogas-based compression-ignition engine-generator plants. The investment cost of the spark-ignition engine-generator plant is higher than the compression ignition engine-generator plant (Stassen, 1995). For example, specific capital investment cost of the 100 kW$_e$ capacity spark-ignition engine-generator and compression ignition engine-generator plant are US\$ 499 and US\$ 419 (September 2004 value), respectively (Stassen, 1995). For 30 kW$_e$ capacity plant, the corresponding costs are US\$808 and US\$688 (September 2004 value), respectively (Stassen, 1995). For the above two cases, specific investment ratio of the spark-ignition and compression-ignition engine-generation plant becomes 1.19 and 1.17 respectively, which can be rounded as 1.2. So, trend equation (6.6) could be adjusted to estimate the specific capital investment of the AD-based compression-ignition engine-generator plant, by dividing a factor of 1.2.

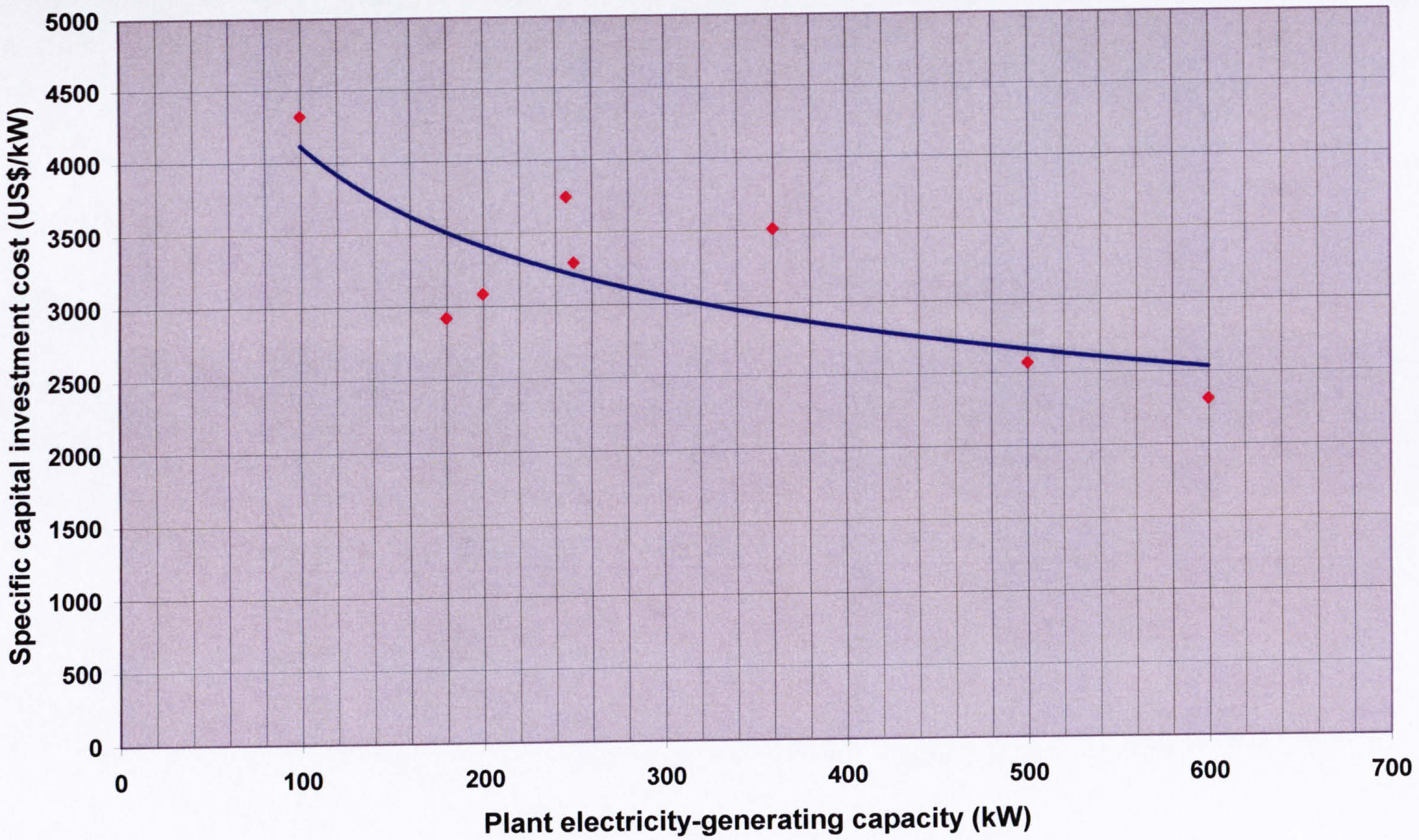


Figure 6.14 Specific capital investment cost of the biomass anaerobic digestion based spark-ignition engine-generator plants in Europe and the USA

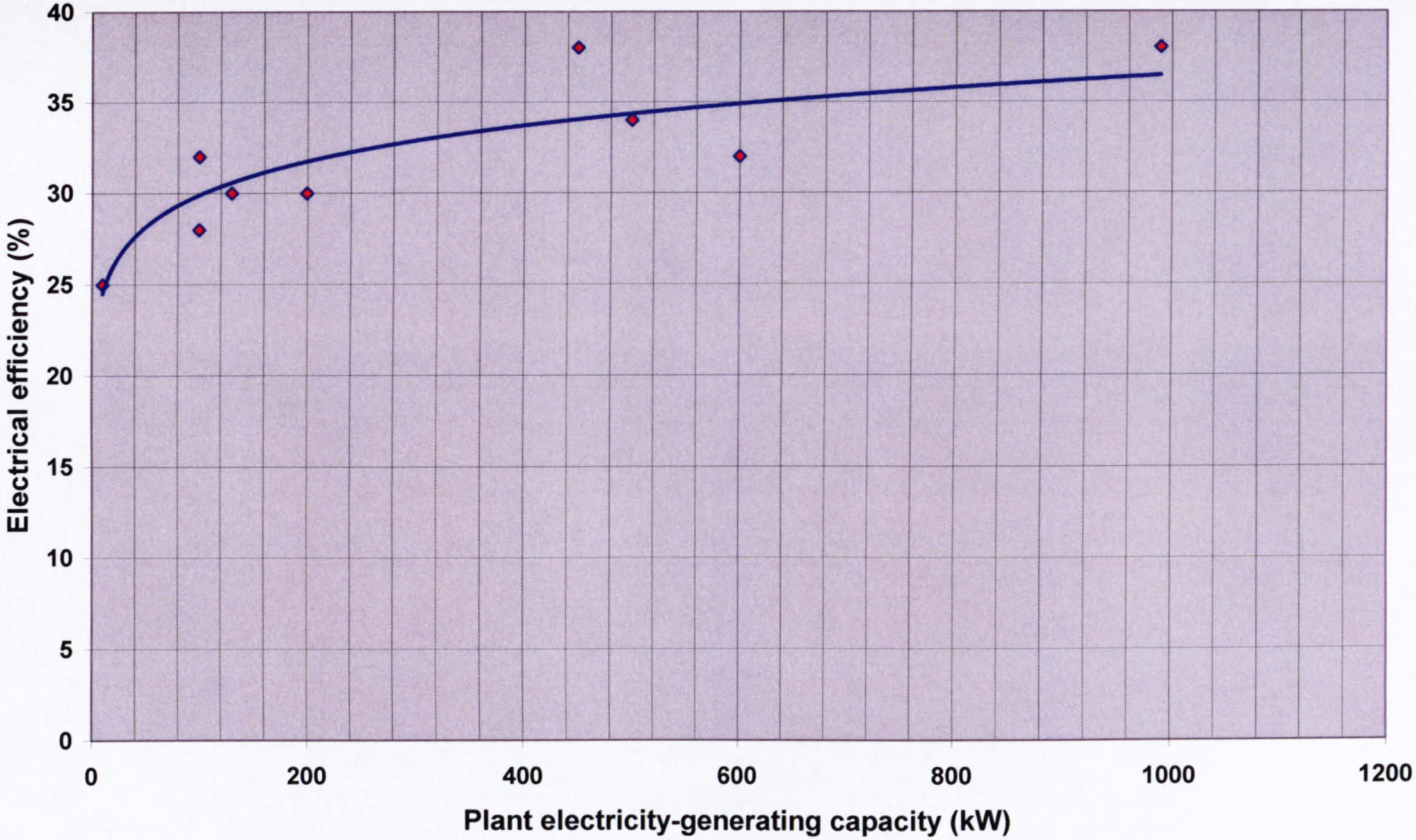


Figure 6.15 Electrical efficiency of the biomass anaerobic digestion based spark-ignition engine-generator plants in Europe and the USA

The electrical efficiency of the gasification-based spark-ignition engine-generator plant is lower than the compression-ignition engine-generator plant (see Table D1, Appendix D). For example, electrical efficiency of the 30 kW_e and 100 kW_e spark-ignition engine electricity-generating plants are 16% and 17% respectively, whereas the corresponding values are 18% and 19% respectively in the case of compression-ignition engine electricity-generating plants (see Table D1, Appendix D). Using these data, electricity efficiency ratio of the gasification-based compression-ignition and spark-ignition generation plant becomes 1.125 and 1.118 respectively; which can be rounded as 1.12. Assuming the similar ratio for biogas-based plants, trend line equation (6.7) could be adjusted by a factor 1.12, to estimate the electrical efficiency of the AD-based compression-ignition engine-generator plant.

The capital investment cost of biogas plant depends on the local situation (Lettinga and Haandel, 2003). The cost of construction of a biogas-based electricity-generating plant depends to a large extent on the cost of labour, and due to the cheap labour in the developing countries, the investment cost of the plant is much cheaper than in developed countries. Also, the cost of construction materials of the digester in developing countries is cheaper than in the developed countries. The extra costs for the treatment of digestate slurries in the developed countries, can be avoided in developing countries, as in most cases this treatment is not necessary due to the absence of environmental legislation.

Adequate data for the capital investment costs of biogas-based electricity generation plants, installed in the developing countries are not available (see Table D3, Appendix D). It was observed that, in the case of the gasifier-based electricity generation plant, the capital investment costs in developed countries is 2 to 3 times higher than the corresponding costs in developing countries (see Table D1, Appendix D). The same factor was assumed to be applicable for the investment costs of the biogas-based electricity generating plant. As an example, in China, the specific capital investment cost of a 315 kW_e biogas-based plant is 1094 US$/$kW_e$ whereas, in USA, the specific capital investment cost of a 360 kW_e biogas-based plant 3511 US$/$kW_e$ (see Table D3, in Appendix D). Ravindranath and Hall (1995) also reported a cost of US$ 1793/kW_e for 5 kW_e anaerobic digestion-based electricity plant installed in India. The specific investment cost (US$/$kW_e$) decreases as the plant size increases (see Table D3, in Appendix D). So, as a conservative estimate, the capital investment costs of biogas-based electricity-generating plants in developing countries were considered to be 50% of the costs incurred in the developed countries.

Assuming a negligible variation in electrical efficiency, trend equation (6.7) could be used for developing countries as well. The mean electrical efficiency of the data used to generate the electricity efficiency trend line for spark-ignition engine-generator plant is 31.89%.

6.4 Direct Combustion

Biomass-based direct-combustion electricity generation plants are not common in developing countries. In developed countries, however, such plants are commonly utilised for large-scale grid electricity systems. There are only a few small-scale direct combustion based biomass electricity plants which are operating for off-grid applications in some of the developing countries (see Table D5, Appendix D).

6.4.1 Biomass Resources for Direct Combustion

Important properties of biomass fuel, for direct-combustion based electricity generation, was reported in section 6.2.1. Excess air factor (λ) is defined as the ratio of the real air supply to the air which is theoretically needed for combustion. The optimum value of λ depends on the type of furnace and type of biomass fuel (Quaak et al. 1999). Adiabatic flame temperature is very sensitive with λ (see Figure 6.16). Effect of MC on adiabatic flame temperature is more compared to ash content (see Figure 6.16).

Direct combustion is best suited to biomass with low MC. Although it is possible to dewater the sewage sludge and animal waste, and then burn it in a boiler to generate electricity, this technology is still under development because of the inherent processing cost (Lewis and Hoecke, 1999).

6.4.1.1 MSW for Direct Combustion

MSW can be utilised as a fuel for direct combustion, with minimal processing (mass burning); or it can undergo moderate to extensive processing before being combusted as refuse-derived fuel (RDF). The technologies are:

(i) Mass burning. MSW is burned with only minor pre-sorting to remove oversize, hazardous, or explosive materials. MSW is not shredded or sized before combustion. The major components of a mass burn facility include:

- MSW receiving, handling, and storage systems
- A boiler and a flue gas cleaning system
- Steam turbine and generator
- A condenser cooling water system
- A residue hauling and storage system

Small mass burn modular facilities are usually prefabricated and shipped fully assembled or in modules to the construction site.

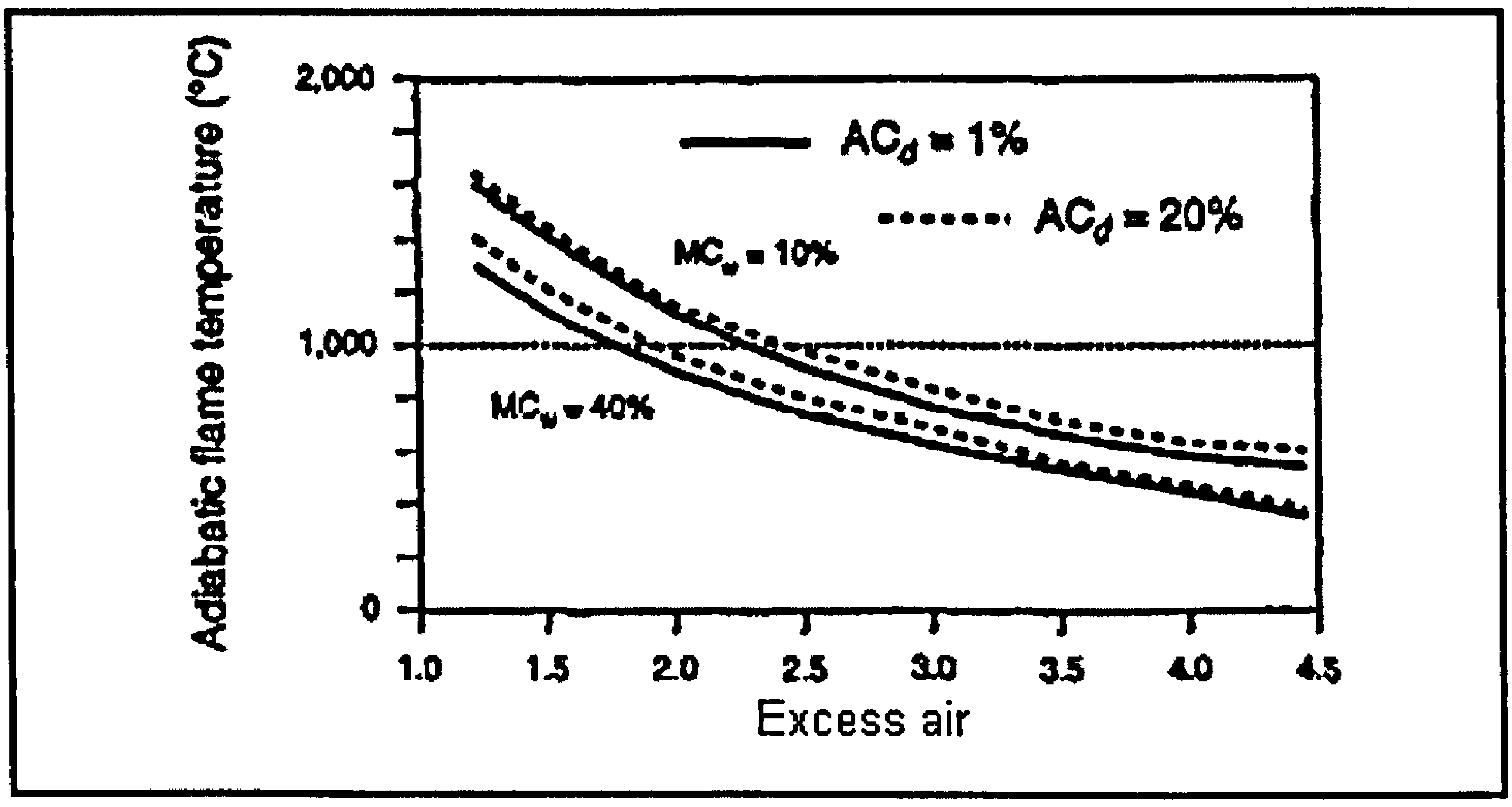


Figure 6.16 Adiabatic flame temperatures as a function of ash content, moisture content and excess air (Quaak et al. 1999)

(ii) Refuse derived fuel (RDF). RDF is produced by mechanically separating the non combustible and recyclable fraction. The extent to which non-combustible materials are removed varies. Most systems remove metals with magnetic separators; glass, grit, and sand are removed through screening. Some systems utilise air classifiers, trommel screens, or rotary drums to further refine the waste. The fuel may be sized for the specific requirements of the furnace or boiler. In some processes, RDF is compressed to pellets or cubes to produce a densified RDF (d-RDF). The RDF can then be used in one of several configurations (CEC, 2002a):

- Dedicated RDF boilers designed with travelling grate or fluidized-bed
- Co-firing of RDF with coal or oil

The combined ash and residue typically ranges from 20 to 25% by mass of the incoming MSW fuel. Production of hazardous ash is avoided by preventing the elements which create hazardous waste, from entering the system. Ash could be mixed with soils for use as land-fill cover (CEC, 2002a).

6.4.1.2 Poultry Litter for Direct Combustion

Poultry litter is usually made up of wood shavings, shredded paper or straw, mixed with the poultry droppings. It has a calorific value of between 9-15 GJ/tonne, and has a moisture content of between 20-50% depending on the methods of husbandry used by farmers (ESRU, 2004). The first commercial-scale poultry litter-based direct-combustion electricity-generation plant was installed in UK (see Table 6.10). No such plant was found in developing countries (see Table D5, Appendix D). District wise availability of poultry waste is not promising to build poultry waste-based direct-combustion electricity-generation plant in Bangladesh (see Chapter 5).

6.4.2 Technology

6.4.2.1 Types of Burner/Combustor

The combustion process consists of: drying, pyrolysis and reduction, combustion of the volatile gases above the fuel bed and combustion of the char in the fuel bed (Quaak et al. 1999). To improve the efficiency of the biomass combustion, pre treatment of the biomass (e.g. chipping, briquetting) is necessary (Wereko-Brobby and Hagan, 1996).

Name	Location of the plant	Year of commissioning	Output capacity (MW_e)	Fuel used	Consumption of fuel (ktonne/yr)	Technology used
Thetford	Norfolk	June, 1999	38.5	Poultry litter	420	Moving grate boiler and steam turbine
Eye	Suffolk	July, 1992	12.7	Poultry litter, horse bedding (12%) and feathers (7%)	160	Moving grate boiler and steam turbine
Westfield	Scotland	January, 2001	9.8	Poultry litter	110	BFB boiler and steam turbine
Glanford	North Lincolnshire	November, 1993	13.5	Meat and bone-meal (MBM)[a]	-	Moving grate boiler and steam turbine

[a] In May 2000 the plant was re-commissioned to burn MBM, can re-commission to combust poultry litter

Table 6.10 Poultry litter combustion-based power plants operating in UK (EPR, 2004)

Generally furnace and the boiler are integrated, and, in practice, such installations are jointly referred to as boiler. Depending on biomass characteristics, different types of boilers are used. For lumps and big pieces having moisture content below 50%, grate firing boiler are used (Quaak et al. 1999). On the other hand, granular biomass (saw dust, rice husk) can be more conveniently burned in a fluidised bed boiler (Quaak et al. 1999). Stoker and fluidised bed boiler technology is in commercial operation at numerous sites throughout the world (see Table D5, Appendix D).

The different types of furnaces/combustors (or boilers) are (Bain et al. 1998; Bhattacharya, 1993; Quaak et al. 1999):

Pile Burner. A pile burner typically consists of a two-stage combustion chamber: a lower pile section for primary combustion and an upper section for secondary combustion. The boiler is located above the secondary combustion chamber. Biomass fuel is piled up on a grate in the bottom. Combustion is completed in the secondary combustion zone. Feed is introduced either on top of the pile or through an underfeed arrangement using an auger. Ash is removed by manually dumping the ash from the grate after the ash is cooled. Pile burners typically have low thermal efficiencies (50 to 60%). It is simple and has the ability to handle wet, dirty biomass fuel.

Stoker combustor. Stoker combustor has a moving grate which permits continuous ash removal, thus eliminating the cyclic operation characteristic of the pile burners. The fuel is spread more evenly, normally by a pneumatic stoker, giving more efficient combustion. In basic stoker design, the bottom of the furnace is a moving grate.

Bubbling fluidized-bed combustor. In this type of combustor, the primary combustion air flows from the bottom. There are two zones; a zone containing freely moving sand particles supported by upward air and a freeboard zone above the fluidised bed. The particles remain suspended in the combustion air due to the balance of downward gravity force and the upward drag force due to flue gas flow. Hot flue gases from an external burner are used to preheat the fluidized bed to the fuel ignition temperature. For biomass, this temperature is around 540^0 C. Combustion is completed in the freeboard space resulting in freeboard temperatures approaching 980°C. The important advantages of BFB boiler include low NO_x formation due to low operating temperature and ability to burn even low grade fuels with high efficiency. For example, rice husk, which can not be burned efficiently in conventional combustion chambers, has been burned with 95-99% thermal efficiency in such beds.

Circulating fluidized-bed. In a CFB boiler, the air velocity is so high that the bed and fuel particles flow upward with the flue gas stream, forming a solid circulation loop. The light fuel particles burn during circulation, whereas the heavy particles burn until they are light enough to join the circulation stream. Heat exchange rates are high because of the intensive mixing in fluidised bed. Combustion temperature ranges from 750^0C to 950^0C. In a CFB boiler, it is easy to introduce a sorbet solid, such as limestone or dolomite, to control SO_2 emissions. CFB temperatures are maintained at about 870°C, which helps to optimize the limestone-sulphur reactions. CFB boiler can handle varying feedstock with different composition, ash contents and moisture contents.

6.4.2.2 Prime movers

The steam/heat generated through direct firing of biomass can be used to drive a steam turbine or steam/Stirling engine. The simplest systems (up to 100 kW_e output capacity) operate on an open cycle requiring a continuous supply of clean water for the boiler (RWEDP, 2002a). Boilers based on a closed cycle generally have higher efficiencies. The smallest available system of this type is of 200 kW output capacities (RWEDP, 2002a).

Stirling engines have been in use for small-scale, direct-combustion, off grid electricity generation. Biomass fired Stirling engine is a feasible technology in the range of 5 to 100 kW output capacities (Podesser, 1999). In this type of external combustion engine, the system is based on closed cycle, where a working gas (e.g. air, helium and nitrogen) is alternatively compressed in a cold cylinder volume and expanded in a hot cylinder volume (see Figure 6.17). Wood–processing industries commonly dump their wood wastes. A trend is now emerging in Indonesia and Malaysia to establish integrated wood-processing complexes, where wood wastes from processing are being used to supply energy for the complex (RWEDP, 2005).

6.4.3 Potential Biomass Resources

It has been proven that BFB and CFB boiler can burn many agricultural, municipal and forestry-based biomass resources (Schmidt and Pinapati, 2000). CFB boiler can burn biomass fuels with MC between 15 to 60% by mass (Schmidt and Pinapati, 2000). Fluidised bed combustor can burn biomass fuel with ash content up to 50% or even higher (Quaak et al. 1999).

From the review of the data presented in Table D5 (in Appendix D) and studying the availability of biomass resources in Bangladesh (see Chapter 5); the biomass resources to be considered for direct-combustion based electricity-generation systems in Bangladesh are:

- Agricultural wastes
- Forestry residues
- Combustible fraction of MSW

Many direct combustion-based electricity-generating plants are designed with multiple type of fuel feeding capability (Schmidt and Pinapati, 2000). Burning of agricultural residues and fuel wood/ forestry residues together to generate electricity has been practised (see Table D3, in Appendix D). The available amount of the agricultural waste and forestry residues were estimated for the whole country and as well as for

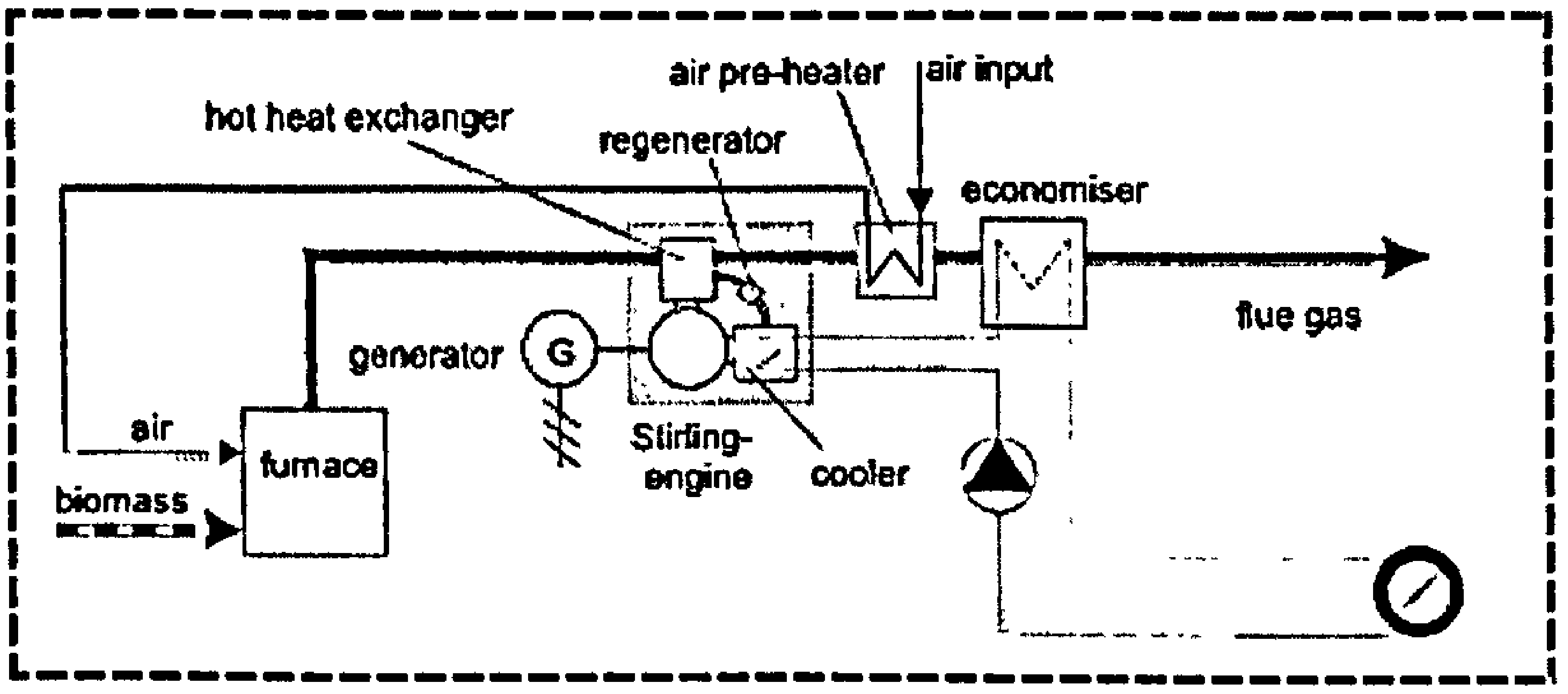


Figure 6.17 Schematic diagram of the Stirling engine operation (Lensu and Alakangas, 2004)

each district (see Chapter 5). District wise availability of either agricultural wastes or forestry residues alone is not promising for direct-combustion based electricity generation (see Chapter 5) in Bangladesh. Mixing the agricultural wastes and forestry residues would ensure the uninterrupted feed supply and generate more electricity for a given district. In Bangladesh, the combustible part of the MSW is 20% by mass of the total available MSW (REIN, 2005e).

Quantities of certain fuel constituents like K, Cl, Si, and S (in the case of agricultural wastes) and Ca and Mg (in case of forestry residues) in the mixed biomass fuel should be controlled before feeding to fluidised bed boiler; otherwise these constituents leads to agglomeration and hard deposition (on the boiler surfaces) by reacting with sand used in fluidised bed, at the boiler operating temperature of 800-900^{0}C (Schmidt and Pinapati, 2000). One way of controlling is by controlling the mixing ratio of the biomass fuels.

So, the potential biomass resources have been grouped for direct-combustion based electricity-generation in Bangladesh, as:

- Group A : Agricultural waste and Forestry residues
- Group B : Combustible fraction of MSW

In case of group A, the energy potential is not uniform in every month due to the seasonal availability of the agricultural residues (see Chapter 5). So, there are two options for utilising the biomass resources of group A:

- Either, to design a plant based on the lowest monthly availability. In this case, there is no need to arrange biomass storage facilities.
- Or, to design a plant based on the average monthly availability. In this case, there should be some arrangement for biomass storage facilities.

The second option was considered in this study for maximum electricity generation potential.

6.4.4 Capital Investment Cost and Overall Efficiency

The components of the capital investment costs of biomass-based direct combustion electricity-generation systems are:

- fuel supply system;
- boiler and gas cleaning system;
- engine or steam turbine;
- auxiliary systems (e.g. condenser, make-up water treatment, boiler feed water pump and flue gas fan);
- generator and control systems;
- land procurement, civil works;
- installation, commissioning and training;

Table D5 (in Appendix D), shows the efficiency, capacity and capital investment costs (US\$/kW$_e$) for different types of the biomass-based direct combustion electricity-generation plants installed in different parts of the world. All the costs were converted into US\$, in September 2004 value (see Section 6.1). The capital investment costs and electrical efficiency varies widely mainly due to the variation of the conversion equipment, types of biomass fuel and plant electricity generating capacity (see Table D5, Appendix D). Trend lines of the capital investment costs and overall electrical efficiency of the direct-combustion based electricity-generation plants were generated (see Figure 6.18 and Figure 6.19), for direct-combustion based steam-turbine generator systems; utilising biomass fuel, either agriculture wastes or forestry residues alone or mixture of agricultural wastes and forestry residues. The best fit equations of the trend lines for the specific capital investment and overall electrical efficiency are:

$$SCI_{\text{steam turbine direct combustion plant}} = -628.87\ln(P) + 8983.8 \tag{6.8}$$

$$\eta_{\text{steam turbine direct combustion plant}} = 3.395\ln(P) - 4.8702 \tag{6.9}$$

Figure 6.20 shows the correlation developed between the electrical efficiency and plant electricity-generating capacity of the direct-combustion based Stirling-engine generator system. Data are not available to generate the trend of capital investment cost. The best fit equation for the electrical efficiency is:

$$\eta_{Stirlingengine} = 18.212(P)^{0.0815} \tag{6.10}$$

Specific capital investment costs of the MSW-based direct-combustion plants are relatively higher, due to the addition of pre-treatment cost of MSW (see Table D5, Appendix D). On the other hand, the overall electrical efficiencies of this type of plants are lower than the plants utilising agricultural residues and fuel wood (see Table D5, in Appendix D). Adequate data are not available to develop the capital investment and efficiency correlations for MSW-based direct-combustion electricity-generating plants. As a close approximation, trend line equations developed for agricultural wastes and forestry-based direct-combustion plants would be used for MSW-based plants. The mean value of the overall electrical efficiency of the MSW based electricity generating plant is around 20% (see Table D5, Appendix D).

The mean electrical efficiency of the data used to generate the electricity efficiency trend lines for direct-combustion steam turbine generator and direct-combustion Stirling-engine generator plants are 24.4% and 24%, respectively.

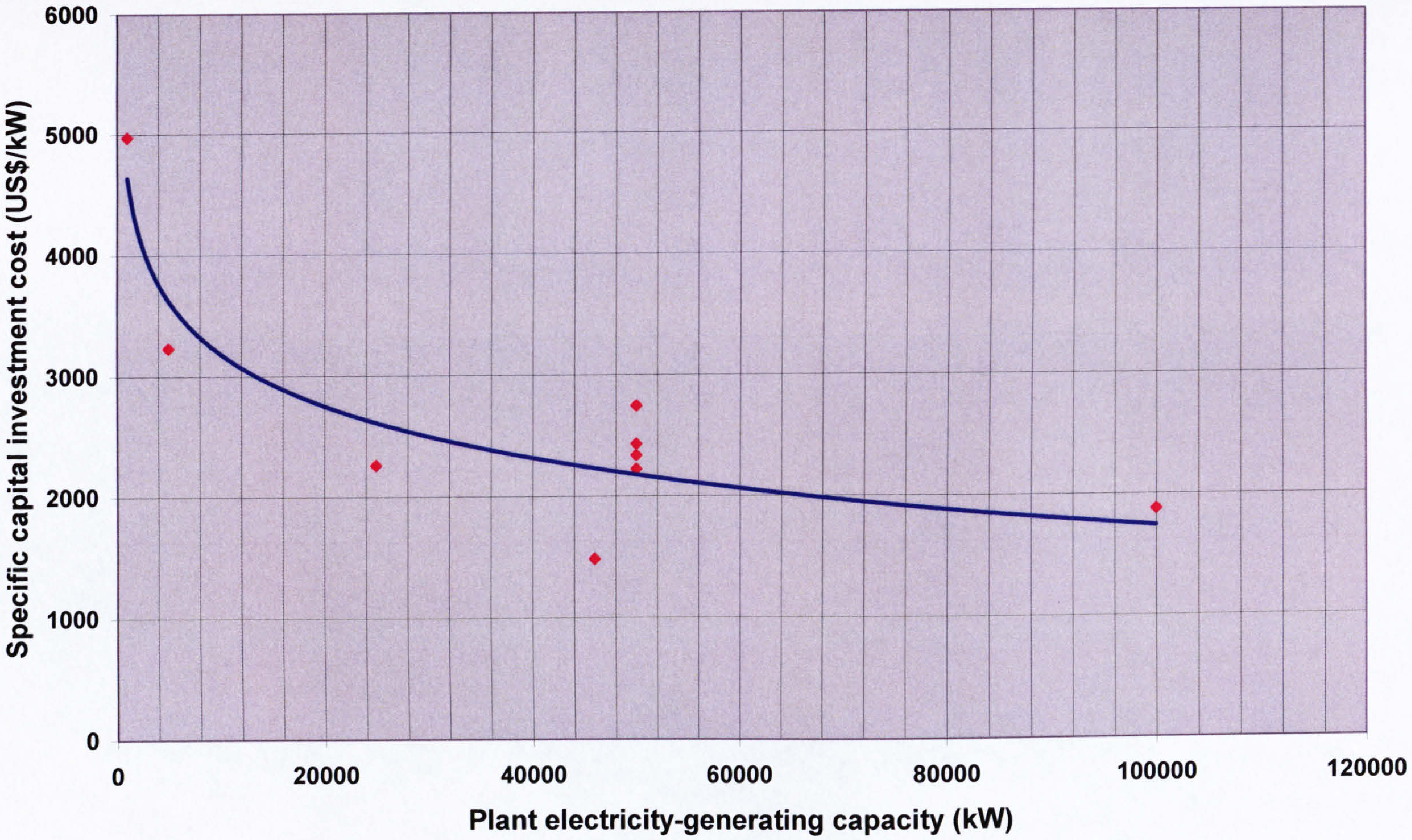


Figure 6.18 Specific capital investment cost of the biomass direct-combustion based steam turbine generator plants

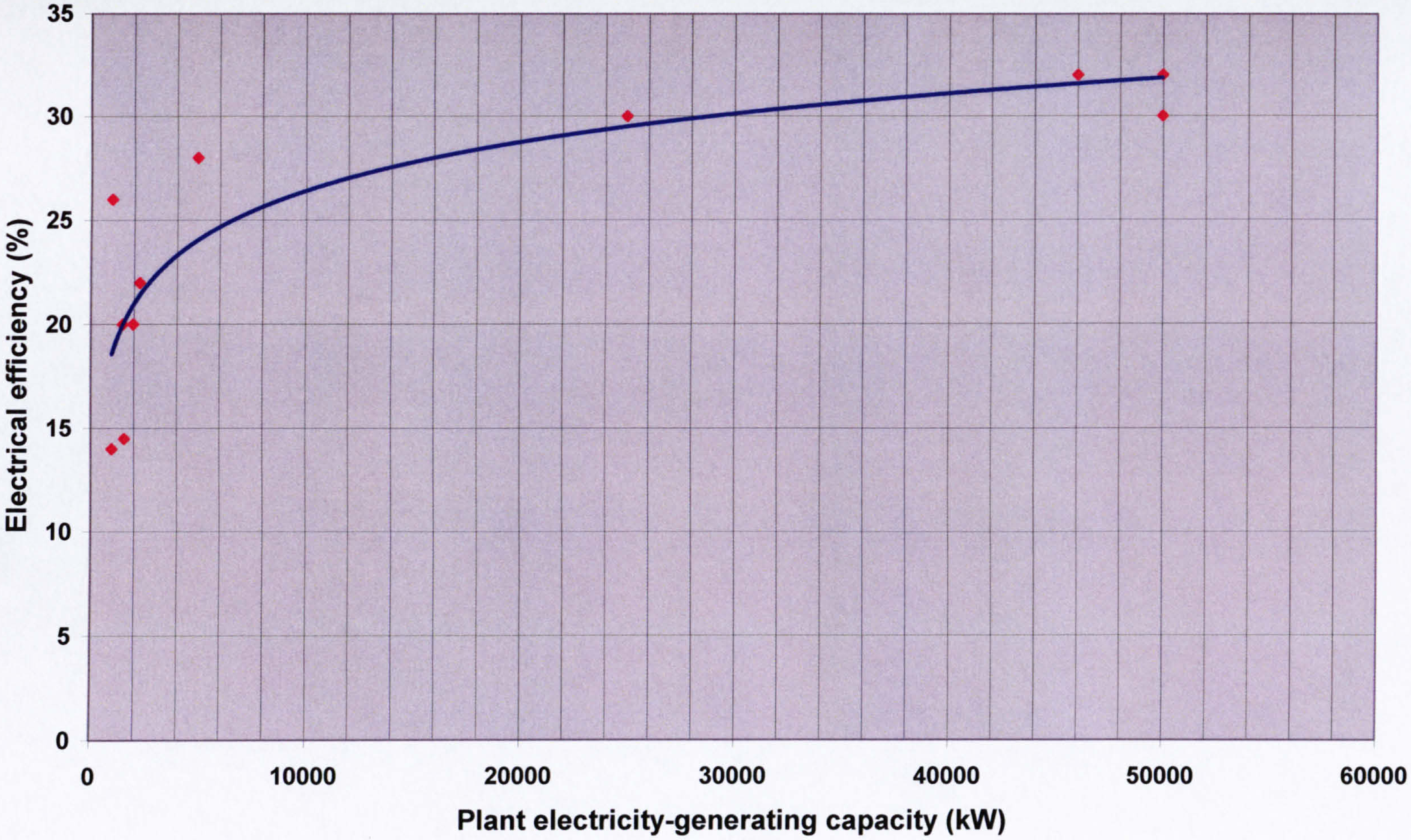


Figure 6.19 Electrical efficiency of the biomass direct-combustion based steam turbine generator plants

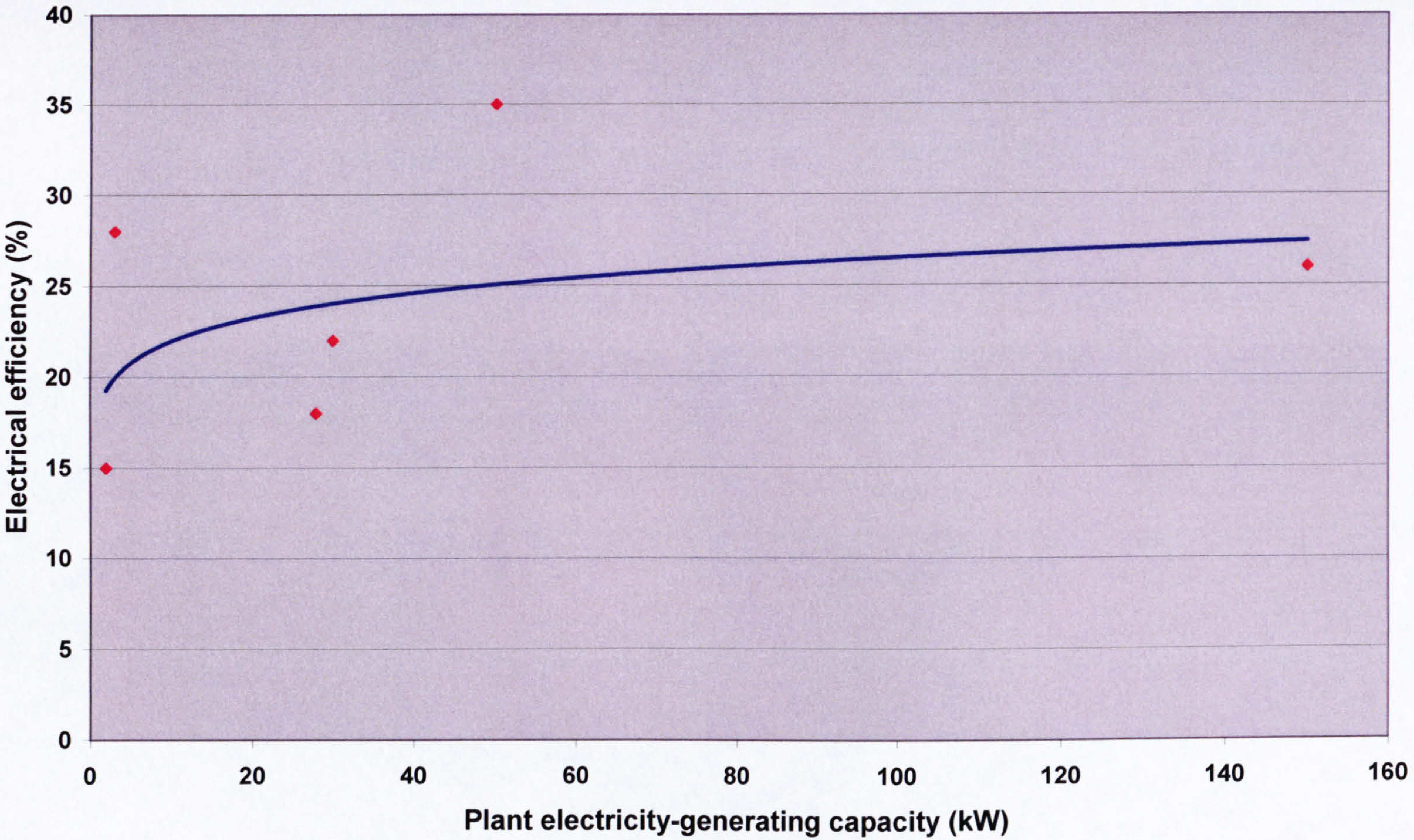


Figure 6.20 Electrical efficiency of the biomass direct-combustion based Stirling-engine generator plant

6.5 Electricity Generation Potential

6.5.1 Operating Hours

Plant operating hour is an important parameter for assessing the potential and economics. This aim of this research is to asses the feasibility of the biomass electricity plants in rural and remote areas, where there is no grid electricity supply. In rural /remote areas, the electricity is used for:

- Household lighting and cooling, lighting the local market
- Small scale commercial : bakeries, hotels/restaurants
- Small scale industries: rice mill, sewing/garments factory
- Deep tube well: irrigation pumps
- Local clinic/hospital, local government offices
- Entertainment: sport activities, cinema, television
- Day schools, clubs and night school for adults

The demand for electricity in household, market, entertainment and night school are in evening periods. On the other hand, for other users, electricity is needed mainly in day time period. So, by arranging proper load management (i.e. matching power supply to demand to maximise the efficiency of the utilised generating resources) the plant could be operated from 10 a.m. till 10 p.m., i.e.12 hrs/day to satisfy the electricity demand of the users.

6.5.2 Total Energy and Electricity Generation Potential

National total energy and electricity generation potential have been estimated (see Table 6.11) for different technology. For gasification and direct-combustion based technology option, energy potential of any specific biomass fuel or mixture of biomass fuel was calculated by multiplying the available amount of biomass fuel in a year with the lower caloric value (or energy content) of that biomass fuel (see Chapter 5). Whereas, in the case of anaerobic-digestion based technology, biogas was considered as fuel, instead of biomass (see Section 6.3.6) for developing the correlations. The amount of biogas generated from the available amount of biomass (in a year) was estimated for both the groups. Energy potential was then calculated by multiplying the total amount of biogas generated with the lower caloric value of biogas (i.e. 20 MJ/m^3).

Technology	Mean electrical efficiency (%)	Biomass utilisation grouping	Energy potential (PJ/year)	Electricity generation potential (TWh/year)
Gasification and spark-ignition engine-generator	16.65	Group A: Ag. wastes and forestry residues[a]	280.95	13.00
		Group B: MSW	20.94	0.96
		Group C: Poultry litter	7.53	0.34
Anaerobic digestion and spark-ignition engine-generator	31.89	Group A: Animal wastes and poultry waste	74.71	6.61
		Group B: Sewage sludge and MSW	46.06	4.08
Direct combustion and steam turbine	24.40	Group A: Ag. wastes and forestry residues[a]	280.95	19.04
	20.00	Group B: MSW	20.94	1.17

[a] based on average availability per month

Table 6.11 National total biomass energy availability and electricity generation potential: by technology

Finally, annual electricity-generation potential was calculated, by multiplying the potential energy with the mean overall electrical efficiency of each technology option. Direct combustion proved the highest electricity generation potential followed by gasification (see Table 6.11).

6.6 Use of Compression Ignition Engines: Cost and Efficiencies

6.6.1 Technology

Diesel engine-driven generators are used widely over the world. Commercial sizes with an electrical output from about 5 kW up to 30 MW are available (ITDG, 2004). Diesel fuel is available in most part of Bangladesh. In remote areas, however, its price is higher than in urban areas due to the addition of transportation costs.

6.6.2 Capital Investment Cost and Overall Efficiency

6.6.2.1 Diesel only Operation

The specific capital investment cost and overall electrical efficiency of the diesel engine-generator set depends mainly on the plant capacity and manufacturer/brand (see Tables D6 and D7 of Appendix D). Correlations between the specific capital investment costs and plant electricity-generating capacity; and between the overall electrical efficiency and plant electricity-generating capacity were developed for diesel generators of mixed brands. The trend lines (see Figure 6.21 and Figure 6.22) were generated as the best fit of the data presented in Tables D6 and D7 of Appendix D:

$$SCI_{\text{diesel generator plant}} = 607.63(P)^{-0.2883} \qquad (6.11)$$

$$\eta_{\text{diesel generator plant}} = 2.6459[\ln(P)] + 20.625 \qquad (6.12)$$

The costs of the diesel engine-generator sets are free on board price. Land procurement, civil works, installation, training and commissioning costs need to be added to know the total specific capital investment cost of this type of plant for economical analysis. The mean electrical efficiency of the data used to develop the efficiency trend is 32.38%.

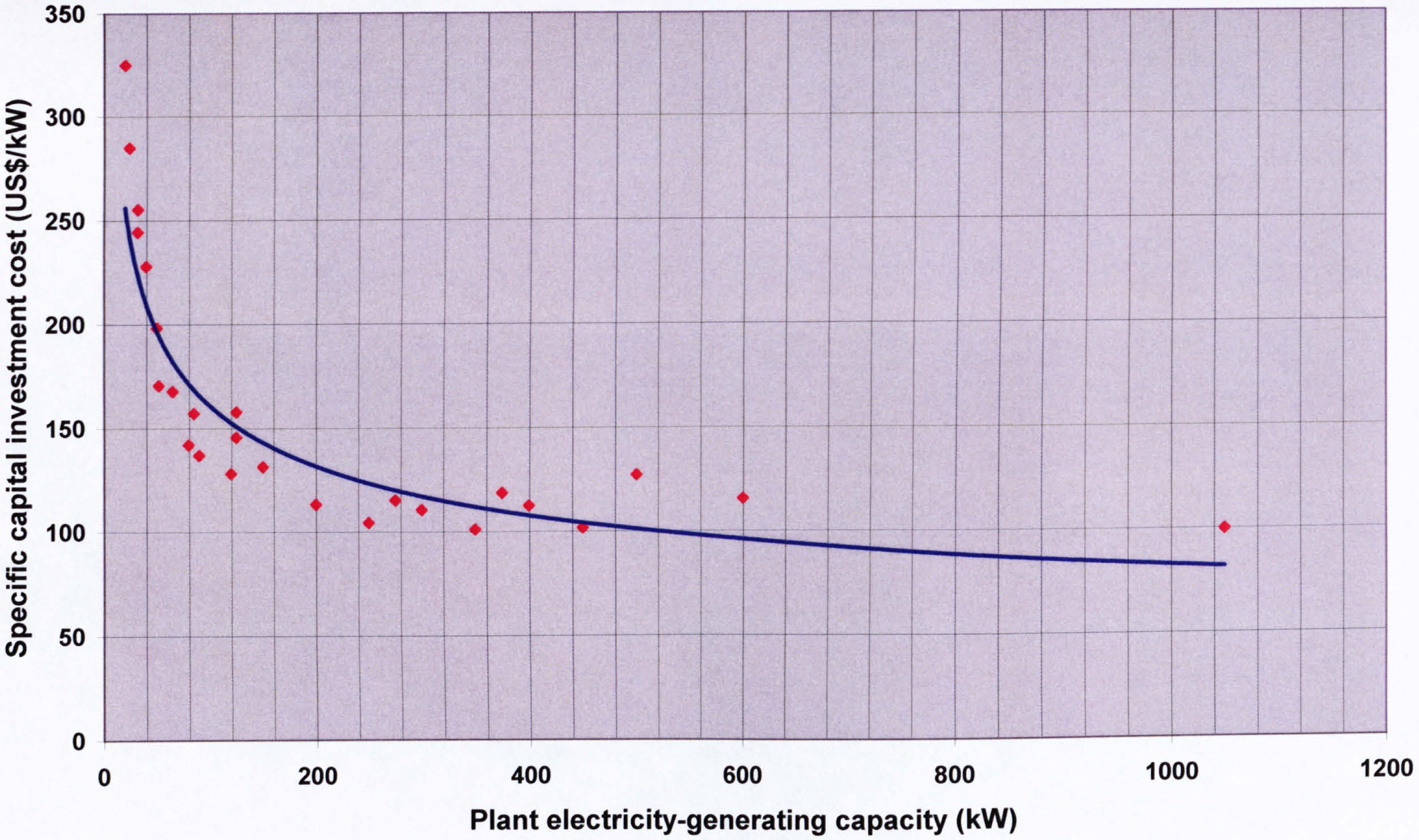


Figure 6.21 Specific capital investment costs of diesel generator sets

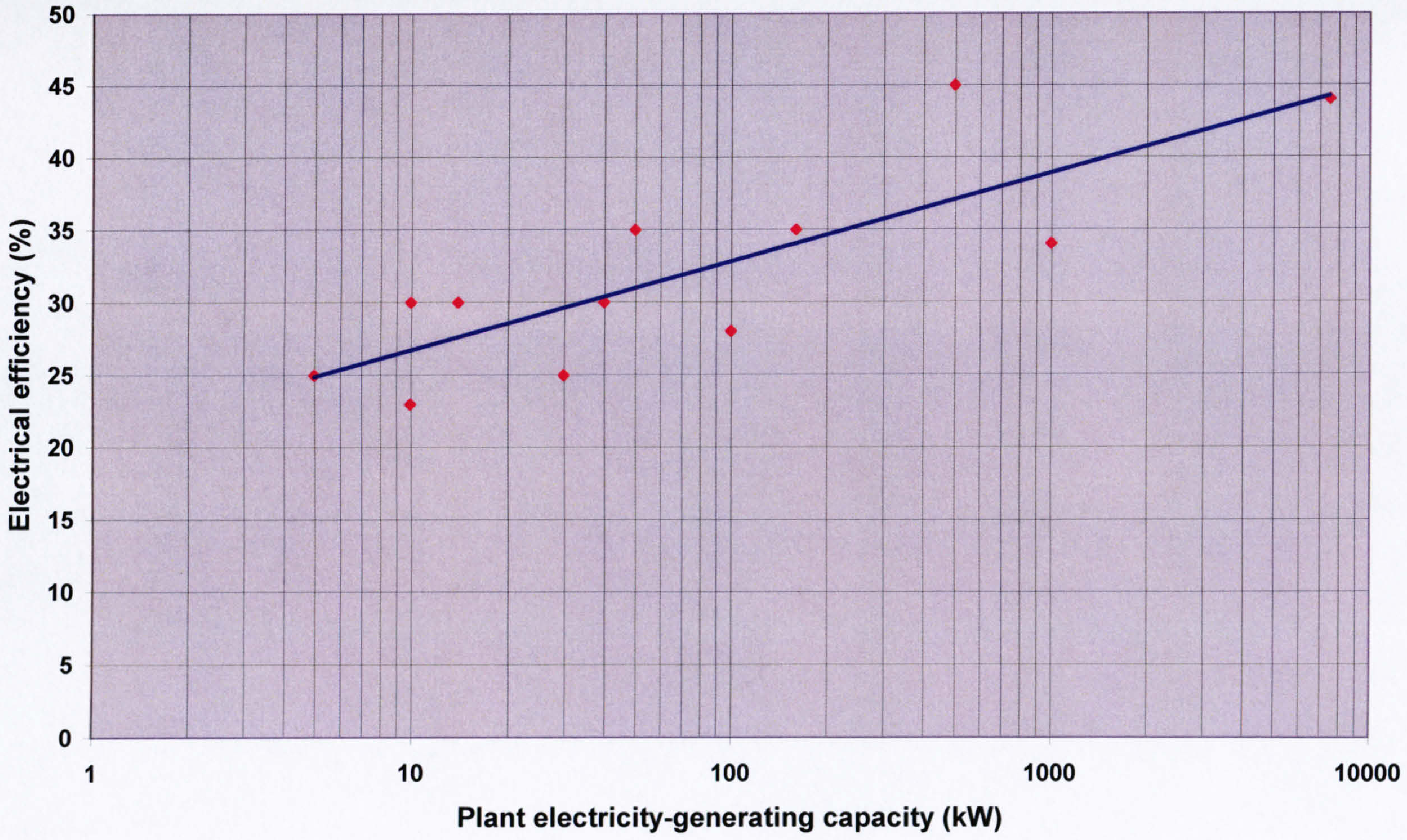


Figure 6.22 Overall electrical efficiencies of the diesel generator sets

6.6.2.2 Dual-fuel Operation

A schematic diagram of a small-scale dual fuelled (diesel and producer gas) compression ignition engine electricity generation system is shown in Figure 6.23. Trend line equations of the electrical efficiency and capital investment cost of the dual-fuelled generator plants operating in dual fuel mode of operation (diesel plus producer gas or biogas) have been developed in section 6.2.5 and 6.3.6 respectively.

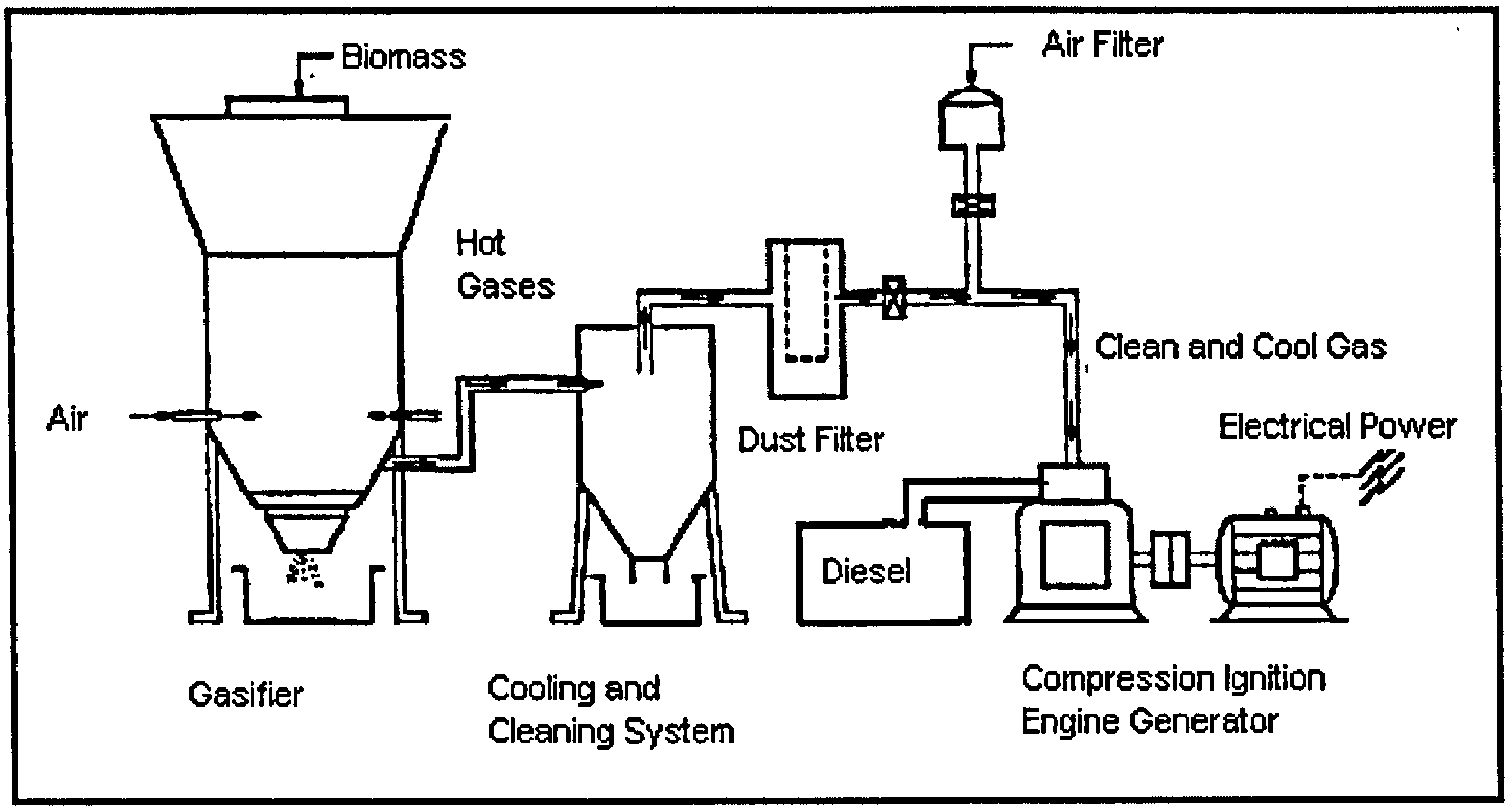


Figure 6.23 Electricity generation in dual-fuel mode (Tripathi et al. 1997)

6.7 Conclusions

This original assessment of the technological feasibility of biomass electricity generation in Bangladesh revealed that feasible technologies are:

- Gasification-based ICE-generator
- Anaerobic digestion-based ICE-generator
- Direct combustion-based steam turbine or Stirling-engine generator

A critical review of these feasible technologies for small- to medium-scale biomass electricity generation has been undertaken. Biomass groupings and utilisation strategies have been developed for each type of the feasible technologies based on biomass availability and properties in order to achieve the maximum electricity generation potential (see Figure 6.24).

Correlations of the capital investment costs and overall conversion efficiency, as functions of the electricity generation capacity, for the feasible technologies selected for small to medium-scale biomass electricity generation have been developed. These can be employed to assess the biomass electricity plant economics in Bangladesh and any other developing country.

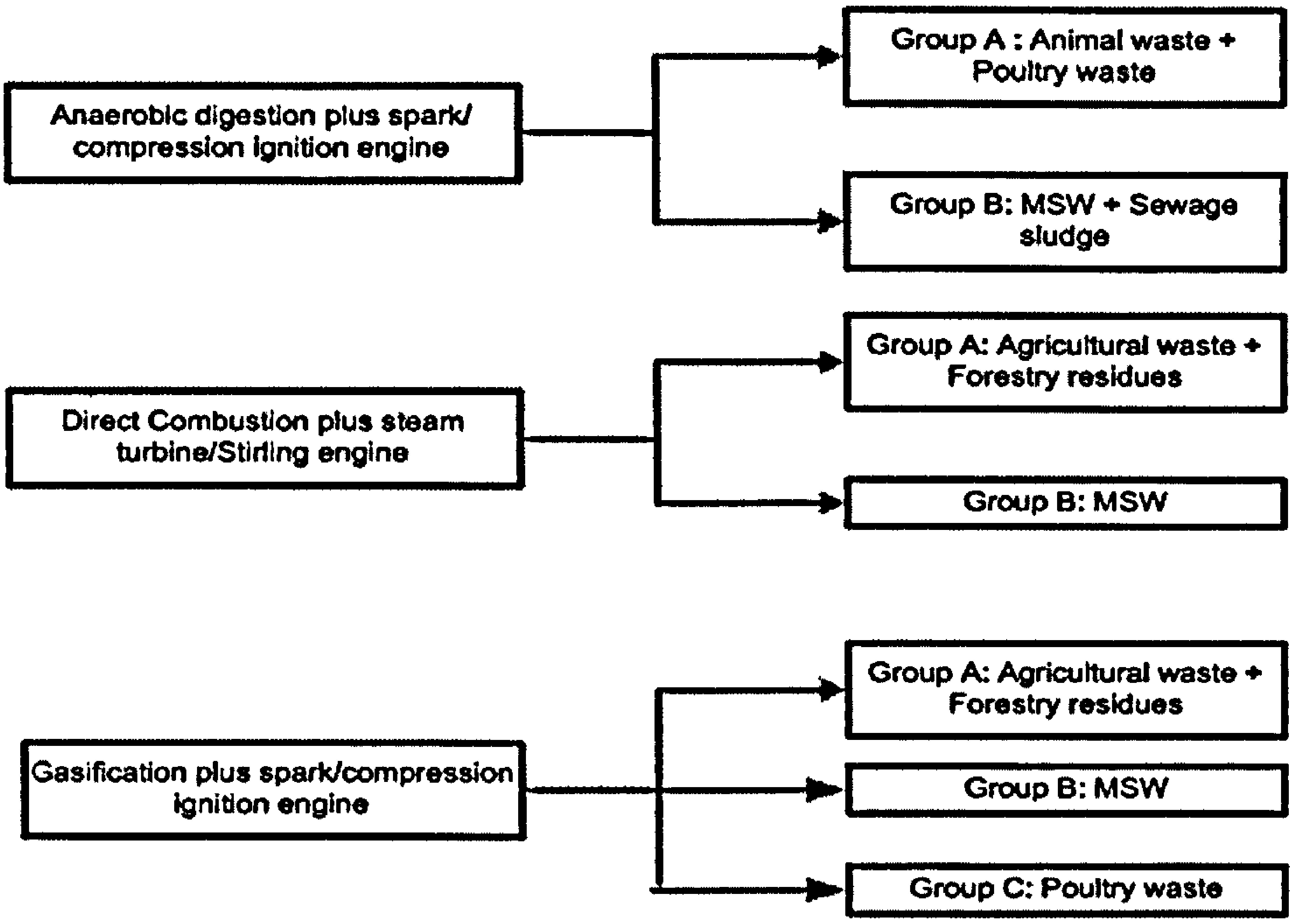


Figure 6.24 Feasible technologies and corresponding biomass resources

Electricity generation potential has been estimated for each individual district (see as an example Appendix E for the districts of the khulna division) as well as the whole of the country (see Appendix F) for each type of the feasible technologies using the mean overall electrical efficiency. For the entire of Bangladesh, the highest annual amount of electricity (i.e. 20.21 TWh) can be generated using the direct combustion technology, followed by gasification (i.e. 14.30 TWh). Anaerobic digestion has the potential to generate 10.69 TWh.

Diesel generators are commonly employed for decentralised electricity generation. For such systems, the capital investment costs and overall conversion efficiency as a function of the electricity generation capacity have also been developed in order to compare the biomass electricity plant economics with the diesel generator plant economics.

CHAPTER 7
SIZING OF BIOMASS ELECTRICITY PLANTS

7.1 Introduction

Biomass energy availability, costs and efficiencies of the technically feasible conversion technologies, and maximum electricity generation potential have been estimated in previous chapters. Electricity generation potential was estimated for national total and as well on district wise basis. The next step is to decide the size of biomass electricity plants. Optimisation techniques have been used to estimate economic plant sizes, economic radius of biomass collection and maximum number of plants (in a district) for different types of feasible technology options.

7.2 Overall Efficiency and Capacity of the Biomass Electricity Plants

The overall conversion efficiency η_0 of the electricity generation plant can be written as:

$$\eta_0 = \frac{E}{Q_b} = \eta_c \eta_e \tag{7.1}$$

Assuming the area of biomass collection to be a circle of radius r (km), with the centre represented by the power plant location, then according to equation (7.1), the average output capacity P of the biomass-energy plant can be written as:

$$P = \frac{E}{t} = \frac{\eta_0 Q_b}{t} = \frac{\eta_0 \sigma \pi r^2 H_b}{t} \tag{7.2}$$

The overall conversion efficiencies of the different types of technically-feasible conversion technologies are estimated in the following sections.

7.2.1 Combined Gasifier/ICE - Generator

There are different options under this technology. These are:

- Gasifier and producer gas-fuelled IC engine
- Gasifier and dual-fuelled IC engine
- Combined gasifier/Gas turbine-generator

7.2.1.1 Gasifier and Producer Gas -fuelled ICE

The overall efficiency of this type of conversion system can be written as:

$$\eta_o = \eta_G \eta_{GE} \eta_e \tag{7.3}$$

The thermal efficiency of the gasifier is defined as:

$$\eta_G = \frac{Q_{sg}}{Q_b} = \frac{m_{sg}H_{sg}}{m_b H_b} \tag{7.4}$$

The gas engine thermal efficiency can be defined as:

$$\eta_{GE} = \frac{W_{UGE}}{m_{sg}H_{sg}} \tag{7.5}$$

7.2.1.2 Gasifier and Dual-fuelled ICE

The thermal efficiency of the engine in dual-fuel operation (i.e. producer gas + diesel fuel) mode (η_{dfe}) is generally less than the efficiency η_d when fuelled by diesel fuel only (Kapur et al. 1996). The overall efficiency of this type of conversion system can be written as:

$$\eta_o = \eta_G \eta_c \eta_e = \eta_G \eta_{dfe} \eta_e \tag{7.6}$$

The thermal efficiency of the dual-fuelled engine can be written as:

$$\eta_{dfe} = \eta_d \, df$$

where, df is a de-rating factor in efficiency due to the employment of the dual-fuel mode of operation

Total energy input to a dual-fuelled engine-generator system to generate 1 kWh of electricity can be expressed as:

$$Q_t = \frac{1}{\eta_{dfe}\eta_e} = \frac{1}{\eta_d \eta_e df} \tag{7.7}$$

The performance of a dual-fuelled engine is characterised by a diesel substitution or diesel savings, which is known as diesel replacement factor (rf). It indicates the proportion of diesel input that is replaced by the second fuel. So the energy input of diesel to the dual-fuelled engine to generate 1 kWh of electricity can be expressed as:

$$Q_d = \frac{(1-rf)}{\eta_d \eta_e} \tag{7.8}$$

If the energy input of the producer gas is Q_g, then:

$$Q_g = \frac{1}{\eta_d \eta_e}\left[\frac{1}{df} - (1-rf)\right] \tag{7.9}$$

The quantities of diesel (M_d) and biomass (M_b) to generate 1 kWh of electricity can be written as:

$$M_d = \frac{Q_d}{H_d} = \frac{(1-rf)}{\eta_d \eta_e H_d} \tag{7.10}$$

$$M_b = \frac{Q_g}{\eta_G H_b} = \frac{1}{\eta_d \eta_e \eta_G H_b}\left[\frac{1}{df} - (1-rf)\right] \tag{7.11}$$

7.2.1.3 Combined Gasifier/Gas turbine

The overall efficiency of this type of conversion system can be defined as:

$$\eta_o = \eta_G \eta_{GT} \eta_e \tag{7.12}$$

The gas turbine cycle thermal efficiency can be defined as

$$\eta_{GT} = \frac{W_{UGT}}{m_{sg} H_{sg}} \tag{7.13}$$

7.2.2 Combined Anaerobic Digester/ICE - Generator

Under this type of technology, there are two options:

- Biogas digester and biogas-fuelled IC engine
- Biogas digester and dual-fuelled IC engine

7.2.2.1 Biogas Digester and Biogas-fuelled ICE

The overall efficiency of the system can be written as:

$$\eta_o = \eta_D \eta_{GE} \eta_e \tag{7.14}$$

The thermal efficiency of the digester is defined as:

$$\eta_D = \frac{\mathrm{Q_{bg}}}{\mathrm{Q_b}} = \frac{m_{bg} H_{bg}}{m_b H_b} \tag{7.15}$$

The gas engine thermal efficiency can be defined as

$$\eta_{GE} = \frac{W_{UGE}}{m_{bg} H_{bg}} \tag{7.16}$$

7.2.2.2 Biogas Digester and Dual-fuelled ICE

Equations, similar to those presented in section 7.2.1.2 for the producer gas and dual-fuelled IC engine, are applicable for this type of conversion technology. In this case, the gasifier would be replaced by the digester.

7.2.3 Direct Burning/Heat Engine- Generator

Either a Stirling engine or steam turbine is used as prime mover.

7.2.3.1 Direct Combustion and Steam Turbine

The overall efficiency of this type of conversion system is:

$$\eta_o = \eta_{ST}\eta_e \tag{7.17}$$

The steam turbine cycle thermal efficiency can be defined as:

$$\eta_{ST} = \frac{W_{UST}}{m_b H_b} \tag{7.18}$$

7.2.3.2 Direct Combustion and Stirling Engine

The overall efficiency of this type of conversion system can be written as:

$$\eta_o = \eta_{SE}\eta_e \tag{7.19}$$

The Stirling engine thermal efficiency can be defined as:

$$\eta_{SE} = \frac{W_{USE}}{m_b H_b} \tag{7.20}$$

7.3 Mathematical Modelling and Optimisation

7.3.1 Mathematical Modelling

Mathematical modeling is a description, in terms of mathematical relations, invariably involving some idealization, of the functions of a physical system (Bejan et al. 1996). System understanding, designing, optimisation, controlling and training are the main objectives of the mathematical modeling of a system (Cross and Moscardini, 1985).

The stages of mathematical modeling are (Cross and Moscardini, 1985):

- Problem Identification.

- The Gestation Stage. It includes the gathering of the background information, acquiring an understanding of the system under consideration, and sorting out relevant data. In this stage, it is very important to recognise that a solution is possible.
- The Model Building (formulation) Stage. Having exposed the important mechanisms and contributory factors, each is considered in turn and described mathematically to some extent. The modeller must ensure that the model matches the available data and within the physical constraints of the system.
- The Simulation Stage. After building the model, it is used to run an experiment to asses what would happen in a hitherto inexperienced situation. A set of simulation runs should be fairly carefully designed to observe the effects of parameter changes and, hence, identify which are the most critical with respect to both design and control.
- The Pay-off Stage. In this stage, one can learn most about the modelling process itself. Having built the mathematical model, made recommendations and then observed either the construction or modification of the system, it is useful for the modeller to make an appraisal of just how well the model performed. In this stage, the modeller makes a balance recommendation regarding operation, design and/or control of the system. This allows one to see and appreciate any conceptual or even computational errors that lingered in the model.

7.3.2 Optimisation

Bejan et al. (1996) described the term optimisation as - the modification of the structure and the design parameters of a system to minimise the total levelised cost of the system products under boundary conditions associated with available materials, financial resources, protection of the environment, and government regulation, together with the safety, operability, reliability, availability, and maintainability of the system.

Optimisation criteria may be economic, technological and environmental. It is desirable to develop a design that is best with respect to more than one criterion. But it is impossible to find a solution that, for example, simultaneously minimises costs and environmental impact while maximising the efficiency and reliability (Bejan et al. 1996).

Selection of the independent variables is very important in formulating an optimisation problem. Types of variables are: the decision variables and the parameters. In optimisation studies, only the decision variables may be varied; the parameters are independent variables that are given one specific and unchanging value in any particular model statement (Bejan et al. 1996).

7.3.2.1 Techniques of Optimisation

The mathematical modeling for an optimisation problem consists of an objective function to be maximised or minimized (Bejan et al. 1996). For a complex optimisation study, it is desirable to break down the study into smaller sub systems and then to optimise the smaller sub systems individually (Bejan et al. 1996). The optimisation method can be categorized according to the nature of the objective function, the constraints, and the decision variables involved. The objective function may:

- contain a single decision variable or many decision variables
- be continuous or contain discontinuities
- be linear or non linear

The most commonly used optimisation techniques are described below (Jelen, 1983; Boas, 1983 and Bejan et al. 1996):

- Optimisation for a single variable

  The available techniques for this type of optimization system are:

  - Analytical or Indirect. Analytical methods deal with the application of calculus. The first derivative vanishes at the optimal value. The sign of the second derivative determines the local maximum or local minimum. If a function is bounded in an interval (constrained function), the boundary points also can qualify as local optima.
  - Graphical or Tabular. It is the most elementary method of finding a maximum or minimum point of an objective function. The graphical method has the advantage of distinguishing between mathematical maxima and minima, inflection points, and the highest and lowest values. By using this method, the user can recognise how responsive the optimum value is, to a variation in the independent variable.
  - Incremental or Direct. The incremental method is instinctive and basic. It amounts to operating at one value of the independent variable, changing the variable somewhat, and determining the calculation or observation, whether the change is advantageous. This method is suitable for trial by experiment. Computers have enabled the application of incremental or direct methods. This method can easily treat problems involving objective functions with discontinuities, points of inflection, and boundary points.

- Linear and nonlinear programing techniques

  In linear programming technique, both the objective function and the constraints are linear. Nonlinear objective function and/or constraints are the most common type encountered in thermal optimization problems. In a problem, in which there are n independent variables and m equality constraints, attempt might be taken initially to solve each of these constraints explicitly for a set of n – m variables, and then express the objective function in terms of these variables. If all the equality constraints can be removed, and there are no inequality constraints, the objective function might then be differentiated with respect to each of the remaining n – m variables and the derivatives set equal to zero.

  There are five major approaches for solving nonlinear programming problems, these are: Lagrange multiplier method, iterative quadratic programming methods, iterative linearization methods, penalty function methods, and direct search methods (Reklaitis et al. 1983; Edgar and Himmelblau, 1988; Papalambros and Wild, 1988; Pike, 1986; Beveridge and Schlechter, 1970).

- Dynamic and Geometric programming

  Dynamic programming is used in the same context as in linear programming. This method decomposes a multivariate interconnected optimisation problem into a sequence of sub problems that can be solved serially. Each of the sub problems may contain one or a few decision variables. Geometric programming optimisation technique can handle a certain form of functions with fractional and negative exponents in an efficient manner (Reklaitis et al. 1983; Edgar and Himmelblau, 1988; Pike, 1986; Beveridge and Schlechter, 1970).

7.3.2.2 Steps of Optimisation

The general steps for formulating an optimisation problem are (Jelen, 1983):

- deciding the exact objective to be optimized
- setting the objective function using as many variables as are required
- setting up all the restraints and relationships between the variables
- reduction of the objective function to independent variables (if possible)
- solution of the objective function. If it contains single dependent variable only, the differentials can be set equal to zero to optimise the expression. Alternatively, if it contains more than one dependent variable in addition to independent variables, a Lagrange expression technique can be tried.

7.4 Optimisation Method Applied to Biomass Electricity Plants

In general, the objectives of any investments are (Schuyler, 1997):

- Build at lowest possible cost
- Build at optimum life-cycle cost
- Build for maximum return on investment

Benefit-cost analysis is a decision making process and this type of analysis is most applicable to public works project. To minimise the costs and maximise the profitability, is the main objective to optimise the design parameters in benefit-cost analysis. The term profitability can be defined as a measure of the total income for a project compared to the total outlay (Jelen and Black, 1983). Profitability measurement can be performed for a short period of time, or for the entire life of a project. The related terms used to measure the profitability are (Redden and Lavingia, 1997; Irvin, 1978):

- Cash Flow (CF): Is the difference of income (inflow) and expenditure (outflow), and counted only at the time they actually occur.
- Discounted Cash Flow (DCF): Method of evaluating an investment by estimating future cash flows. In this method, the time value of money is considered.
- Net Present Value (NPV): NPV is the sum of the present values of all positive and negative cash flows, i.e., it is the present worth of the total profit of an investment. If NPV is positive, the investment is economically viable; if it is negative, the investment is not economically viable. It is considered desirable when NPV adequately remunerates the investment made.
- Return on Investment (ROI): ROI or Internal Rate of Return (IRR) is a measure of profitability of any plant. IRR is defined as the interest rate that equates the present value of the future receipts of a project to the initial cost. Alternatively, it is the discount rate, at which $NPV = 0$. It is also known as Discounted Cash Flow Rate of Return.

- Simple Payback Period: Another technique used to measure the profitability is the Payback Period (PBP), which is the time needed to get back the investment. It can be estimated as:

$$\text{PBP} = \frac{\text{Total investment}}{\text{Annual Income (sales - operating cost)}}$$

7.4.1 Application

A mathematical relationship with the radius of biomass collection as a design variable and the profitability as the objective function has been developed, which is applicable for all types of the feasible biomass electricity conversion technologies. Analytical method of optimisation for single variable has been used to maximise the profitability.

The Profitability Index (PI) defines the profit or loss of the investment operation per unit of total investment. PI is also known as Discounted Return on Investment. For assessing the investment proposals, IRR was a favourite ranking index in the 1960s. The PI is now recognised as more theoretically correct (Schuyler, 1997). PI is defined as:

$$PI = \frac{\text{Present value of the cash flows}}{\text{Original amount invested}} = \frac{NPV}{I} \qquad (7.21)$$

NPV can be calculated by discounting CF over the useful life of the plant by a present worth factor. Annual cash flow, NPV and present worth factor can be calculated as:

$$\text{Annual Cash Flow} = CF = CI - CO \qquad (7.22)$$

$$\text{NPV} = CF * f_a - I \qquad (7.23)$$

$$f_a = \frac{(1+i)^n - 1}{i(1+i)^n} \qquad (7.24)$$

(i) Cash Inflow from Sale of Biomass electricity

The selling income of the electricity generated can be written as:

$$CI = ES_{ue} = Q_b \eta_0 S_{ue} = \sigma \pi r^2 H_b \eta_0 S_{ue} \qquad (7.25)$$

(ii) Cost of Purchasing the Biomass

$$C_b = \sigma \pi r^2 C_{bs} \qquad (7.26)$$

(iii) Cost of Transporting the Biomass

If dr is a width of a little strip at a circular distance of r, then the amount of biomass available in that strip is:

$$dw = \sigma 2\pi r dr$$

The cost of transportation for transporting dw tonnes of biomass to the centre of the circle is:

$$dC_t = 2C_{ts} r \sigma \pi r dr$$

If the transportation distance is not radial, then a constant b (>1) is applicable to use as the ratio of actual road length to the direct radial distance, so the above equation can be written as:

$$dC_t = 2C_{ts} \sigma \pi b r^2 dr \qquad (7.27)$$

By integrating equation (7.27), the equation for total transportation cost is:

$$C_t = \int_0^r 2\sigma \pi b C_{ts} r^2 dr = \frac{2}{3} \sigma \pi b C_{ts} r^3 \qquad (7.28)$$

(iv) Cost of Operation

$$C_w = C_{ws} N_u \qquad (7.29)$$

(v) Cost of Repair and Maintenance

$$C_r = I k_r \qquad (7.30)$$

(vi) Cost of Storage

$$C_s = C_{ss} W_s \qquad (7.31)$$

(vii) Others fixed cost (Overhead Cost)

This includes infrastructures repair and maintenance, staff training/entertainment of visitors, and management expenses. This can be expressed as:

$$C_f = I k_f \qquad (7.32)$$

So, substituting all the cash flow terms, the equation (7.22) can be written as:

$$CF = (ES_{ue}) - (C_b + C_t + C_w + C_r + C_s + C_f) \qquad (7.33)$$

Consequently, using equation (7.21), (7.23) and (7.33), PI can be written as:

$$PI = \frac{\left[ES_{ue} - \left(C_b + C_t + C_w + C_r + C_s + C_f\right)\right]f_a - I}{I} \tag{7.34}$$

Substituting all the cash inflows and cash out flows in equation (7.34):

$$PI = \left[\sigma\pi r^2 H_b \eta_0 S_{ue} - \left(\sigma\pi r^2 C_{bs} + \frac{2}{3}\pi r^3 b\sigma C_{ts} + C_{ws}N_u + Ik_r + C_{ss}W_s + Ik_f\right)\right]\frac{f_a}{I} - \tag{7.35}$$

Using the equation 7.2, total investment cost can be written as:

$$I = I_s P = \frac{\sigma\pi r^2 H_b \eta_0 I_s}{t} \tag{7.36}$$

Substituting I in equation (7.35) and rearranging, PI can be written as:

$$\begin{aligned}
PI &= \frac{f_a t S_{ue}}{I_s} - \frac{f_a t C_{bs}}{H_b \eta_0 I_s} - \frac{2bf_a t C_{ts} r}{3H_b \eta_0 I_s} - \frac{f_a t C_{ws} N_u}{\sigma\pi r^2 H_b \eta_0 I_s} - f_a k_r - f_a k_f - \frac{f_a t C_{ss} W_s}{\sigma\pi r^2 H_b \eta_0 I_s} - 1 = \\
&\left(-\frac{f_a t C_{ws} N_u}{\pi\sigma H_b \eta_0 I_s} - \frac{f_a t C_{ss} W_s}{\pi\sigma H_b \eta_0 I_s}\right) r^{-2} + \left(-\frac{2bf_a t C_{ts}}{3H_b \eta_0 I_s}\right) r + \left(\frac{f_a t S_{ue}}{I_s} - \frac{f_a t C_{bs}}{H_b \eta_0 I_s} - 1 - f_a k_r - f_a k_f\right) = \\
&\left(-\frac{f_a t}{\pi\sigma H_b \eta_0 I_s}\left(C_{ws} N_u + C_{ss} W_s\right)\right) r^{-2} + \left(-\frac{2bf_a t C_{ts}}{3H_b \eta_0 I_s}\right) r + \left(\frac{f_a t S_{ue}}{I_s} - \frac{f_a t C_{bs}}{H_b \eta_0 I_s} - 1 - f_a k_r - f_a k_f\right)
\end{aligned} \tag{7.37}$$

The above equation can be written as:

$$PI = Ar^{-2} + Br + C \tag{7.38}$$

where,

$$A = \left(-\frac{f_a t}{\pi\sigma H_b \eta_0 I_s}\left(C_{ws} N_u + C_{ss} W_s\right)\right)$$

$$B = \left(-\frac{2bf_a t C_{ts}}{3H_b \eta_0 I_s}\right)$$

$$C = \left(\frac{f_a t S_{ue}}{I_s} - \frac{f_a t C_{bs}}{H_b \eta_0 I_s} - 1 - f_a k_r - f_a k_f\right)$$

Assuming the term A, B and C are constant for specific type of biomass electricity conversion technology plant and for specific type of biomass resources at a given location, equation (7.38) can be written as $PI = f(r)$. Equation (7.38) shows that the second derivative of PI with respect to r is negative. So, the value of r (r_e) at which PI is maximum can be found by differentiating PI and putting the result equal to zero:

$$\frac{d(PI)}{dr} = 0$$

which results in

$$r = \sqrt[3]{\frac{2A}{B}} \cong r_e$$

or

$$r_e = \sqrt[3]{\frac{2A}{B}} = \sqrt[3]{\frac{3(C_{ws}N_u + C_{ss}W_s)}{\pi b\sigma C_{ts}}} \tag{7.39}$$

If the proposed plant does not need any biomass storage, then $C_{ss} = 0$, so the equation (7.39) can be written as:

$$r_e = \sqrt[3]{\frac{3C_{ws}N_u}{\pi b\sigma C_{ts}}} \tag{7.40}$$

If the distance of the biomass transportation is radial (i.e. b =1), the equation (7.39) and (7.40) can be written as:

$$r_e = \sqrt[3]{\frac{3(C_{ws}N_u + C_{ss}W_s)}{\pi\sigma C_{ts}}} \tag{7.41}$$

$$r_e = \sqrt[3]{\frac{3C_{ws}N_u}{\pi\sigma C_{ts}}} \tag{7.42}$$

Corresponding biomass collection area can be calculated as:

$$A_e = \pi r_e^2 \tag{7.43}$$

The electricity-generating capacity of the plant can be written as:

$$P_e = \frac{\eta_0\sigma\pi r_e^2 H_b}{t} \tag{7.44}$$

7.5 Biomass Electricity Plant Sizing

Feasible conversion technologies and corresponding biomass resources have been discussed in Chapter 6. Due to the seasonal availability of the agricultural residues (see Chapter 5), storage facilities are needed for agricultural wastes and forestry residues-based plants. On the other hand animal wastes, poultry wastes and MSW does not require any storage facilities. Since the size of the plant would determine the amount of storage, so it is difficult to estimate the cost of storage at this stage. As a first approximation, it has been assumed that the effect of storage cost on plant sizing is negligible.

Economic plant sizes and other parameters have been calculated for each type of the feasible conversion technologies using equations (7.42) to (7.44). The mean efficiencies (see Chapter 6) have been used to calculate the economic plant sizes. Later, the economic sizes were corrected by using the Correlations developed for the efficiencies (see Chapter 6) and are defined as corrected plant sizes.

For anaerobic digestion-based biomass electricity plant, the efficiency data used in Chapter 6 and in Appendix D was the electrical efficiency of the biogas operated ICE-generator plant. So, for calculating the overall efficiency of the anaerobic digester-based ICE-generator plant, the thermal efficiency data of the digester is needed, which can be estimated as:

$$\eta_D = \frac{\text{Biogas generation rate} * \text{Calorific value of the biogas}}{\text{Energy content of the biomass mixture}} \tag{7.45}$$

The lower calorific value of 20 MJ/m^3 (see Chapter 6) has been used for biogas, generated from both the groups of biomass resources. Using equation (7.45), typical result shows that thermal efficiency of digestion of group A and group B types of biomass are 43% and 39%, respectively. The thermal efficiency of the anaerobic digester reported in the literature is in the range of 30 - 50% (Paul, 2004; Lusk, 2005; Vijayaraghavan et al. 2003), which logically verifies the estimation used in this study.

Biomass availability densities (σ) were calculated in Chapter 5. Lower caloric value (H_b) or energy content of the biomass resources are reported in Section 7.5.1. Hours of plant operation have been discussed in Chapter 6. Values of other parameters (i.e. C_{ts}, C_{ws}, N_u) have been estimated based on the general experiences in Bangladesh.

It was observed that after deducting the present consumption of the biomass resources, some of the district does not have enough agricultural and forestry resources to use it for electricity generation purposes. In this study, the figure zero was used for the district which does not have enough agricultural wastes and forestry residues for electricity generation potential.

7.5.1 Energy Content of Mixed Biomass Resources

For co-gasification and co-combustion, energy content of the mixed biomass resources can be calculated based on the availability ratio. If W_i is the quantity of i^{th} mixed biomass component and H_i is its corresponding lower calorific value, then the average Lower calorific value of a biomass mixture fuel H_{av} containing a number z of components can be calculated as:

$$H_{av} = \sum_{i=1}^{z} H_i W_i \Big/ \sum_{i=1}^{z} W_i \tag{7.46}$$

and the expected energy content of the mixed biomass fuel is

$$E = H_{av} \sum_{i=1}^{z} W_i \tag{7.47}$$

7.5.2 Default Parameters

The plant would be operated from 10 a.m. till 10 p.m. at night (see Chapter 6), i.e. 12 hrs/day (or 4380 hrs/year); this same number of operating hours has been used for all types of feasible technology. The type of transportation system of biomass fuel and costs depends on the infrastructures and the living standard of the people. This varies from country to country; and even from one region to another region in the same country. The transportation costs also depend on whether the study site situated in rural or urban area. In most developing countries the transportation of biomass is carried out by the following ways:

- Manually (human transportation)
- Transportation by bullock cart
- Transportation by human driven three wheeler (Human Hauler)
- Transportation by truck (and tractor)

Adequate information on transportation costs is not available. Hence estimates had to be made. The transportation cost of the agricultural wastes has been reported as US$ 0.70/tonne per km (Lin et al. 1998). In Bangladesh, due to the availability of cheap labour resources, the cost of the transportation is not high. Actual transportation distance is not radial. Considering this, a typical transportation cost of US$ 1/tonne/km has been estimated based on the experiences in Bangladesh (see Table 7.1).

The same cost data has been used for all types of biomass transportation. Stassen (1995) estimated the number of operators as 2 for 10-100 kW_e capacity gasification-based biomass electricity plants. Tripathi et al. (1997) estimated the number of operators as 2 and 3 for 40-200 kW_e and 300-500 kW_e capacity gasification-based biomass electricity plants, respectively. The activities of the operators in the gasification based plants and direct combustion based plants are almost similar. Whereas, the activities of the operators are more in the case of anaerobic digestion based plants because of the additional activities of the operation and controlling the different parameters of the biogas plant. So, it is reasonable to estimate the number of operators as 3 and 5 for gasification (or direct combustion) and anaerobic digestion based plants, respectively. The wages rates of the operators have been estimated based on the experiences in Bangladesh (see Table 7.1).

7.5.3 Results

Sample results of economic plant parameters are shown in Table 7.2 to Table 7.4 for gasification-based electricity-generation plant. Khagrachari, Dhaka and Feni districts have been selected for group A, group B and group C types of biomass respectively. These districts have been selected considering the biomass availability density potential, remote areas and demand for electricity (see Chapter 2 and Chapter 5). Results of other districts are available from the programme written in Matlab (see Appendix B and Appendix E).

Parameters	Unit	Conversion Technology[a]
		Gasification/ Direct Combustion/ Anaerobic Digestion
Generating hours	(hrs/day)	12
	(hrs/yr)	4380
Cost of transportation	(US$/tonne/km)	1
No. of operators/employees	-	3(5)
Cost of operator/labour	(US$/capita/yr)	1000

a: data in bracketed figure is for anaerobic digestion based plant

Table 7.1 Default parameter values: technical and financial

The details of the biomass resources for respective districts and the results obtained are presented below.

(i) Group A:

The division, districts, types of biomass and technology are:

Name of the division : Chittagong
Name of the district : Khagrachari
Types of biomass : Agricultural wastes and forestry residues
Type of technology : Spark-ignition engine-generator

Parameters	Unit	Value
Biomass availability density (average)	(tonne/km^2/month)	37.98
Mean overall electrical efficiency	(%)	16.65
Total electrical energy potential in the district	(TWh/yr)	0.89
Economic radius	(km)	1.85
Economic capacity of the plant	(kW)	814.08
Area of biomass collection	(km^2)	10.70
Number of the plants	-	252.00
Corrected overall electrical efficiency based on economic capacity using the trend line equation	(%)	17.21
Corrected capacity of the plant	(kW)	829.71

Table 7.2 Economic and corrected values of gasification based electricity generation using agricultural wastes and forestry residues

(ii) Group B:

The division, districts, types of biomass and technology are:

Name of the division : Dhaka
Name of the district : Dhaka
Types of biomass : MSW
Type of technology : Spark-ignition engine-generator

Parameters	Unit	Value
Biomass availability density	(tonne /km^2/yr)	86.47
Mean overall electrical efficiency	(%)	16.65
Total electrical energy potential in the district	(TWh)	0.11
Economic radius	(km)	3.21
Economic capacity of the plant	(kW)	549.17
Area of biomass collection	(km^2)	32.41
Number of the plants	-	45.00
Corrected overall electrical efficiency based on economic capacity using the trend line equation	(%)	17.07
Corrected capacity of the plant	(kW)	563.18

Table 7.3 Economic and corrected values of gasification based electricity generation using MSW

(iii) Group C:

The division, districts, types of biomass and technology are:

Name of the division : Chittagong
Name of the district : Feni
Types of biomass : Poultry waste
Type of technology : Spark-ignition engine-generator

Parameters	Unit	Value
Biomass availability density	(tonne /km^2/yr)	8.72
Mean overall electrical efficiency	(%)	16.65
Total electrical energy potential in the district	(TWh/yr)	0.005
Economic radius	(km)	6.90
Economic capacity of the plant	(kW)	185.86
Area of biomass collection	(km^2)	149.58
Number of the plants	-	6.00
Corrected overall electrical efficiency based on economic capacity using the trend line equation	(%)	16.72
Corrected capacity of the plant	(kW)	186.58

Table 7.4 Economic and corrected values of gasification based electricity generation using poultry waste

The sample results of the economic plant sizes are in the ranges of 200~800 kW (see Table 7.2 to Table 7.4), which matches well within the current practises of the biomass electricity plants in many developing countries (see Appendix D). Results show that the economic size of plant depends greatly on the biomass availability density. If the biomass availability density is higher, the plant size is also high. There are little variations between the corrected and economic plant sizes, which prove the effectiveness of the developed correlations. The corrected plant size would be used as a reference plant sizes for diesel and dual-fuelled generator plants

7.6 Conclusions

A generalised equation of economic radius of biomass collection has been developed for the maximisation of the profitability index. The equation is applicable for all types of the feasible biomass electricity generation technologies in Bangladesh. Economic plant sizes have been calculated using the biomass energy available within the economic radius and the estimated average overall electrical efficiency for each type of feasible technology. Appendix E presents the economic radius of biomass collection and economic plant size for each type of feasible technology option, in the districts of the Khulna division. The economic plant sizes calculated are within the range of plant capacities currently in operation. Economic plant sizes were corrected using the correlations developed in chapter 6. These however are very close to the economic plant sizes.

CHAPTER 8
ECONOMICS OF BIOMASS ELECTRICITY PLANTS AND SENSITIVITY ANALYSIS

8.1 Introduction and Methodology

In this chapter, economics of the biomass based electricity generation for different types of feasible technologies have been assessed. The economical parameters considered are: cost of electricity generation (CoE), simple PBP, NPV and PI.

Figure 8.1 shows the methodology used for economical analysis. Major inputs of economical analysis are: economic plant size, biomass availability density, electrical efficiency, capital investment cost and operating cost.

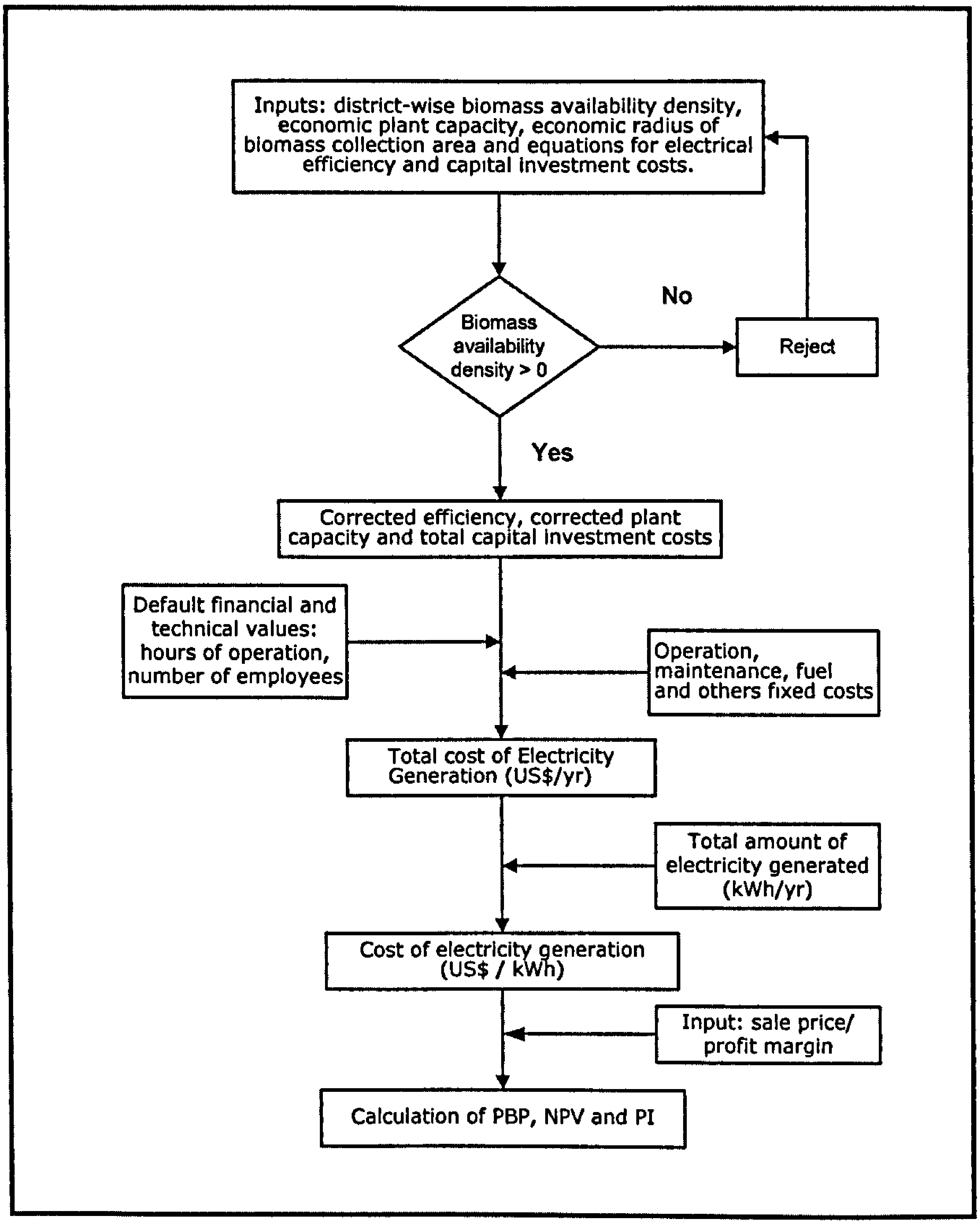


Figure 8.1 Methodology showing district wise calculations of plant economics

Trend equations of conversion efficiency and capital investment costs developed in Chapter 6 have been used in this chapter. For a specific technology option, the corrected efficiency was calculated by using the economic plant size. This corrected efficiency was used to calculate the corrected plant size. This corrected plant size was used for economical analysis. Annual amount of electricity generated was estimated by multiplying the corrected plant capacity with the annual operating hours of the plant. CoE (in US$/kWh) was calculated by dividing the total cost of electricity generation with the annual amount of the electrical energy generated. An estimated selling price of electricity has been proposed by reviewing the literature. Later, PBP, *NPV* and *PI* of the different technology options have been calculated to assess the plant economics.

Diesel generators are popular for small-scale off-grid electricity generation. In the case of gasification or anaerobic digestion-based biomass electricity generation, two possible options of technology were considered, these are:

- Purely biogas/producer gas based spark ignition engine-generator
- Dual fuelled (biogas/producer gas and diesel) based compression ignition engine-generator

The economics of diesel and dual fuelled electricity generation have also been calculated and the results compared with the economics of pure biogas or pure producer gas based electricity generation (see Figure 8.2). On the other hand, economics of the direct combustion based biomass electricity generation technologies system have been compared with the economics of diesel generation system.

Through this economical analysis, it is possible to select the most economical electricity generation option in a specific district for specific biomass. Programmes have been written in Matlab to calculate and compare the economics of different technology options in all 64 districts of the country. A sensitivity analysis has been performed at the end of this chapter.

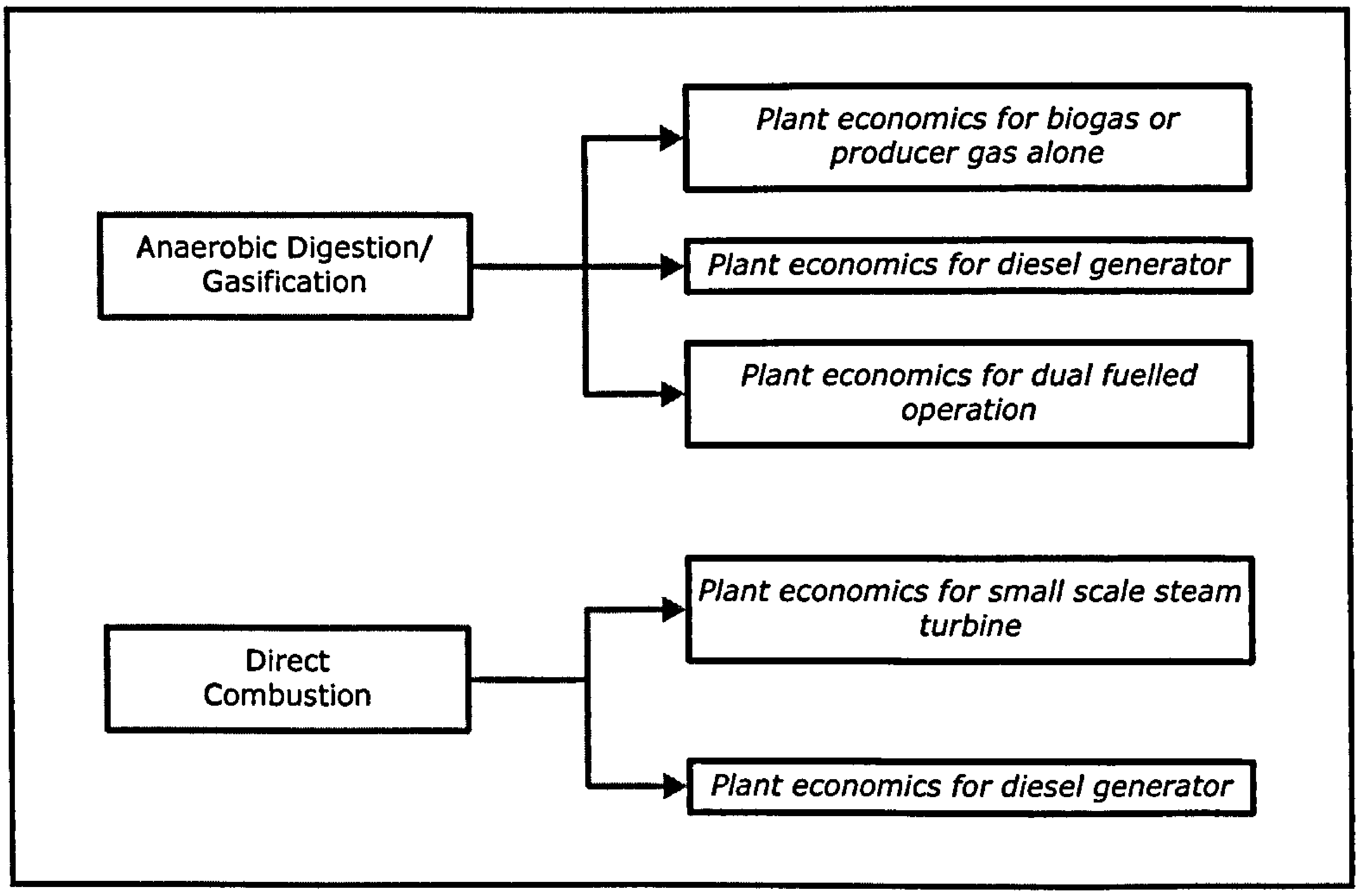


Figure 8.2 Comparison of plant economics

8.2 Biomass Resources and Technology

Feasible biomass electricity conversion technologies and corresponding biomass resources have been discussed in Chapter 6. Economic analysis has been performed for all types of feasible technologies and for all biomass groupings (see Figure 8.3). So, for any specific district, same biomass resources have been used for more than one type of biomass electricity conversion technologies to assess plant economics.

8.3 Elements of Costs

The different elements of costs are discussed in Chapter 7. The total cost of electricity generation (TCoE) and the cost of electricity generation (CoE) can be calculated as:

$$\text{TCoE} = AC + OC + MC + FC + OFC \quad \text{(US\$/yr)} \tag{8.1}$$

$$\text{CoE} = \frac{AC + OC + MC + FC + OFC}{E} \quad \text{(US\$/kWh)} \tag{8.2}$$

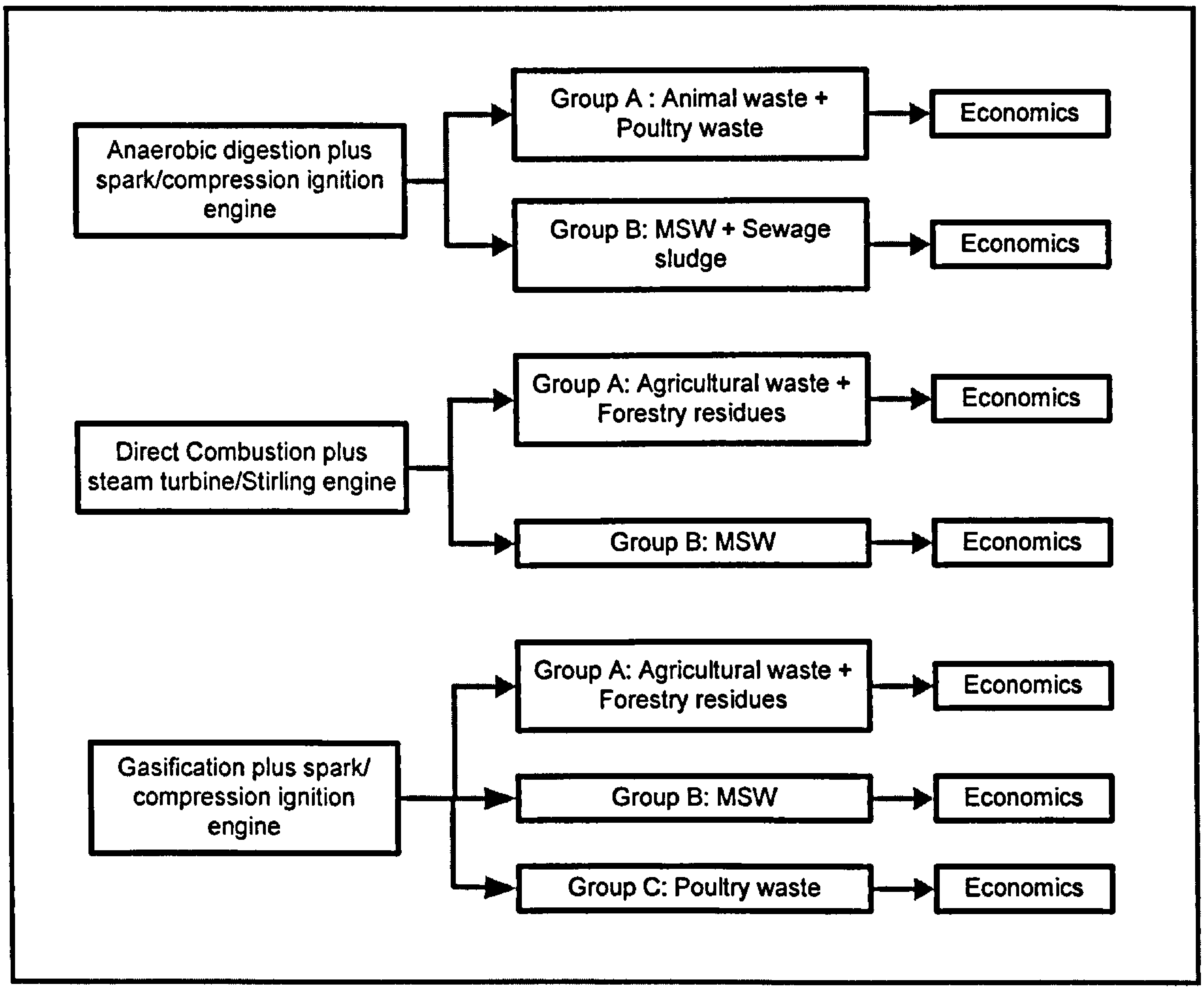


Figure 8.3 Technologies and biomass resources for economical analysis

Simple PBP is the basic tool to compare the different investment projects. The better investment is the one with the shorter PBP. There are two main problems with the PBP measuring technique, these are:

- It ignores any benefits that occur after the payback period and
- It ignores the time value of money.

NPV accounts for the time value of money by expressing future cash flows in terms of their value today. When choosing among mutually exclusive projects, the project with the largest (positive) *NPV* should be selected. The profitability index (PI) is determined by dividing the *NPV* of each proposal by its initial investment. *PI* is known as benefit-cost ratio. The higher the *PI* number, the more financially attractive is the proposal. Simple PBP, *NPV* and *PI* have been calculated using the equations presented in Chapter 7. Present worth factor (f_a) was used to calculate the *NPV* and *PI*. The factor can be calculated as:

$$f_a = \frac{[(1+i)^n - 1]}{i(1+i)^n} \tag{8.3}$$

8.3.1 Cost of Capital

The levelised cost method has been used to assess the plant economics. The levelised cost is a constant annual cost that is equivalent in present value terms to the actual capital and variable costs of the project. Capital recovery factor (CRF) allows investment costs incurred in the construction phase of a plant to be discounted. *CRF* is defined as the ratio of the uniform end-of-period payment or receipt continuing for the coming n periods to the present sum of money. It is also known as the annuity rate and the amount depend on the real interest rate and lifetime of the plant. The *CRF* and the annual amount of the cost of the capital investment (AC) can be calculated as:

$$CRF = \frac{i(1+i)^n}{[(1+i)^n - 1]} \tag{8.4}$$

The term real interest rate is defined as the rate at which the investor gets loan from the bank for investment minus the inflation rate.

$$\text{Annualised capital investment cost} = AC = I\ CRF \quad \text{(US\$/yr)} \tag{8.5}$$

8.3.2 Cost of Repair and Maintenance

Operation and maintenance (O&M) cost is the sum of the operation, repair and maintenance costs, which mainly depends on plant specific conditions (e.g. type and size of the plant, type of fuel). Table 8.1 shows the operation and maintenance costs of the different types of the biomass electricity plants.

Number of operators varies with the types of conversion technology systems (see Chapter 7). In this study, since different types of electricity conversion technology systems has been studied; so, it would be more appropriate to calculate the cost of operation and cost of repair and maintenance separately. Also Table 8.1 shows the data of the two types of costs separately.

Most investigators reported that the annual operation and maintenance cost is in between 5–6% of the capital investment costs (see Table 8.1). The repair and maintenance costs are estimated as a percentage of the yearly investment costs (BIOS, 2004). Mitchell et al. (1995) reported the annual maintenance costs of only 2.5% of the capital investment costs. Kumar et al. (2003) reported the cost as 3% of the capital investment cost. So, in this study, a typical value of 3% of the capital investment costs has been used for repair and maintenance cost for all types of feasible technologies. A similar value has been used for diesel generator plant.

8.3.3 Cost of Operation

Elements of the cost of operation for different types of biomass electricity plants have been estimated in Chapter 7 for calculating the economic plant size.

For the same plant capacity, the number of operators is more in biomass electricity plants than in diesel generator plant. This is due to the additional work involved in the biomass electricity plants (e.g. fuel preparation, adding fuel and filter cleaning). The number of operators has been estimated as 3 and 5 for gasification (or direct combustion) and anaerobic digestion based plants (see Chapter 7). Stassen (1995) estimated that 1 operator is required for 10-100 kW_e diesel generator plant operation. In this study the size of the most diesel generator plants considered are in the range of 300-500 kW_e. So, it is quite reasonable to assume the number of operators as 2 for diesel generator plant operation. The total cost of operation has been calculated by multiplying the wages rate of the operator with the total number of operators.

8.3.4 Cost of Biomass Fuel

The price of biomass varies, the reasons are:

- Variation of biomass sources
- Cost of collection and transportation (infrastructures dependent)
- Local demand for conventional use
- Quantity of production
- Government assistant/subsidy for biomass generation

The cost of biomass fuel (FC) at the plant gate is the sum of the followings:

- Cost of biomass at production site
- Cost of transporting the biomass at the plant site
- Cost of storage and
- Cost of pre-treatment of biomass

Conversion technology	Type of biomass resources	Electricity generating capacity (MW)	O&M costs in 2002 (€ /kW/year)	O&M costs in September 2004 (US$/kW/year)	O & M costs as percentage of capital investment costs (%/ year)	Reference
Anaerobic digestion	-	0.10	250	263	6.0	Kranzl et al. (2004)
		0.25	180	190	5.6	
		0.50	130	137	5.2	
	Sewage gas	0.10	165	174	4.9	Kranzl et al. (2004)
		0.20	145	153	4.8	
		0.60	115	121	5.1	
Direct combustion	Agricultural and forestry products and residues	1.00	135	142	5.4	Kranzl et al. (2004)
	Agricultural residues	1.00	135	142	5.2	Kranzl et al. (2004)
	Biodegradable fraction of MSW	1.00	165	174	2.9	Kranzl et al. (2004)
	Fuel wood	0.10	12^a	14.3	-	Shukla (1998)
			0.0045^b	0.0054		
	Fuel wood	1.00	10^a	11.9	-	Shukla (1998)
			0.003^b	0.004		
Direct combustion/ Gasification	-	1.00	-	-	5.0^e	Quaak et al. (1999)
	Fuel wood	20.00	-	-	2.5^e	Mitchell et al. (1995)
	Producer gas / biogas	0.10	0.018^c	0.020	-	CBO (2003)
Compression ignition engine-generator	-	0.02 – 10.00	$0.005 - 0.015^d$	$0.005 - 0.015^d$	-	DG (2005)
Micro gas turbine generator	-	0.03 – 0.40	$0.008 - 0.015^d$	$0.008 - 0.015^d$	-	DG (2005)
		0.10	0.015^c	0.017	-	CBO (2003)

a: fixed O& M costs in US$/kW/year (1997 value); b: O & M costs in US$/kWh (1997 value); c: in US$ / kWh (2000 value); d: in US$/kWh (March 2005 value); e: only maintenance cost.

Table 8.1 Operation, repair and maintenance costs of biomass electricity plants

8.3.4.1 Cost of Production and Transportation

Some biomass resources are available free (e.g. human excreta, poultry waste and water hyacinth). Agricultural wastes and forestry residues incur costs of production, collection (i.e. transportation cost) and some form of pre-processing (e.g. drying, chipping, baling, and briquetting) costs. Similar transportation costs data, which were used for calculating the economic sizes of the plants, has been used for calculating the plant economics.

8.3.4.2 Cost of Storage and Pre-treatment

Some biomass resources are available all year round (animal waste, forestry residues). But most agricultural residues are only available during and after a brief period of harvesting. Seasonal availability of the different types of agricultural wastes in Bangladesh has been discussed in Chapter 5. Monthly average available amount of agricultural wastes have been used for calculating the plant capacity and economics. For ensuring uninterrupted electricity supply all year round, storage of these resources is needed.

The quantity of the agricultural residues need to storage (tonne/year) and the time period of the storage are the two important factors. These factors depend mainly on the monthly availability of the biomass resources and the requirement rate of the biomass electricity plant. In some months, the amount of available agricultural residues is less than the average amount and in some other months the availability of agricultural residues are more than the average. In June, there is no harvesting of the major agricultural crops in Bangladesh (see Chapter 5). So, in every month it is important to ensure that the average amount of biomass is available all year round. For back up and reliability of biomass supply, the actual quantity needed to be stored should be higher than the theoretical amount of biomass needed.

If space is available and the weather condition allows, the attractive option is to perform the pre-treatment (sizing, drying) and storage, at the production site of the biomass resources (Junginger, 2000). Pre-treatment costs vary with the type and quantity of feed to be processed and the amount of pre-treatment required for certain types of conversion technology. Typical values of the storage and pre-treatment costs of some biomass resources are shown in Table 8.2, which were used for a case study in Thailand. All the costs have been converted to US$ of 2004 value by taking into consideration of inflation rate.

Biomass resources	Density (kg/m^3)	Average storage period (month)	Storage costs (US$/tonne/ month)	Pre-treatment (shredding/chipping) costs (US$ /tonne)	Total costs (US$/tonne)
Rice straw	140	5	5.51	4.50	10.01
Sugarcane tops and leaves	147	3	2.98	1.76	4.74
Wood logs	500	1	0.31	2.76	3.01
Waste wood	500	1	0.31	2.76	3.01

Table 8.2 Storage and pre-treatment costs (in September 2004 value) (Junginger, 2000)

8.3.4.3 Cost of Biomass at Plant Gate

Biomass cost data available in the literature represents the total cost at plant gate and is expressed as either energy basis or mass basis. Shukla (1998) reported the price of biomass as 0.5 to 4 US$/ GJ. Quaak et al. (1999) estimated an average price of biomass of US$ 40/tonne (equivalent to US$ 2.82/GJ). It has been estimated that in Khon Kaen province of Thailand, the average price of most-processed based residues (rice husk, sugarcane bagasee, sawdust, eucalyptus bark) varies between 1.3 US$/GJ to 2.4 US$/GJ (October 2004 value) (Junginger, 2000). This variation is due to the assumed transportation costs and increased demand on biomass by other applications. Typical price of biomass in some Asian countries is shown in Table 8.3. All the costs have been converted to US$, in September 2004 value. For biomass fuels which are available free, only transportation and storage/pre-treatment (if needed) costs would be the price of biomass at the plant gate. Cost of forestry residues are higher than the cost of agricultural residues; for example price of fuel wood and rice husk are US$ 43/tonne and 13 US$/tonne respectively (see Table 8.3).

By reviewing the biomass price data presented in Table 8.3, an average price of US$ 30/tonne has been estimated for the mixed biomass (agricultural wastes and forestry residues) resources in Bangladesh. MSW can be used without any pre treatment for anaerobic digestion. On the other hand, pre-treatment is necessary to use MSW either for gasification or for direct combustion. There are no production and storage costs associated with the utilisation of the MSW. So, the price of the combustible parts of MSW would be less than the price of mixed biomass (agricultural wastes and forestry residues). A typical price value of US$20/tonne has been estimated for MSW either for gasification or for direct combustion.

The price of the biomass resources such as sewage sludge, MSW (untreated), poultry waste and animal waste is only associated with the transportation costs only. Using equation (7.28) of Chapter 7, the price of these biomass has been estimated in US$/tonne as $\frac{2\pi r_e^3 C_{ts}}{3A_e}(=\frac{2}{3}r_e C_{ts})$ (see Table 8.4). Transportation cost (C_{ts}) was estimated as US$ 1/tonne/km (see Chapter 7) for any types of biomass resources.

Country/ year	Biomass resources	Costs[a] (per tonne)	Costs in September 2004 value (US$/tonne)	Reference
Indonesia /1990	Agricultural residues	INR 8000–48000 = US$ 3.5 – 19.2	4.40 – 60.00	RWEDP (2002a)
Bangladesh/ 1996	Fuel wood	BDT 2000 = US$ 39	43.00	Banu (1996)
China /1998	Wood waste	US$ 36	42.00	Zhenhong et al. (1998)
China /1998	Corn stalk and cob	US$ 25	29.00	Zhenhong et al. (1998)
China /1998	Rice husk	US$ 11	13.00	Zhenhong et al. (1998)
China/1998	Agricultural wastes	Yuan 110 = US$ 13.2	15.30	Lin et al. (1998)
China/2002	Rice husk	Yuan 80 = 9.6	10.24	Wu et al. (2002)
India/1996	Agricultural wastes and forestry residues	US$14.08	16.95	Tripathi et al. (1997)

INR Indonesian Rupee; BDT: Bangladeshi Taka

[a] conversion of INR to US$ is based on latest available currency conversion data of year 1995

Table 8.3 Cost of biomass in some Asian countries

Types of biomass resources	Price of biomass (US$/ tonne)
Agricultural waste and forestry residues (mixed biomass)	30
Combustible parts of MSW	20
Animal waste/ Poultry waste/ Sewage sludge	$\frac{2}{3}r_e C_{ts}$
MSW (untreated)	$\frac{2}{3}r_e C_{ts}$

Table 8.4 Estimated price of biomass at the plant gate in Bangladesh

8.3.5 Others Fixed Costs

The elements of the others fixed costs are reported in Chapter 7. Mitchell et al. (1995) estimated this cost as 2.5% of the capital investment cost per year for large scale (20 MW) biomass electricity plants. Kartha and Larson (2000) used this cost as 2% of the capital investment cost per year for a 10 MW biomass electricity plant. In this study, the size of the biomass electricity plant considered is in the scale of kW, so a lower value would be appropriate. Typical figure of 1% of the capital investment cost per year have been used as others fixed costs.

8.4 Economics for Diesel and Dual-fuel Mode of Operation

Same methodology which was used for biomass electricity plants has been applied to calculate the economics of diesel and dual-fuelled electricity generator plants. Correlations developed for efficiency and cost with the plant electricity generating capacity of diesel and dual-fuelled (diesel and biogas/producer gas) engine-generator systems (see Chapter 6) have been used for economical analysis.

The plant electricity generating capacity either for diesel or dual-fuelled generator has been considered same as the plant size (i.e. corrected plant size) used for pure biogas or producer gas based plants.

8.4.1 Diesel Fuel Operation

GOB imports diesel at a cost of BDT 28/litre (~US$ 0.46/litre), but sells the same at BDT 23/litre (~US$ 0.38/litrer) (GCC, 2005). Increase in the price of diesel would affect the agricultural sector in the country. GOB is counting loss every year to keep the diesel price at a low rate. Lower heating value of diesel is 42820 KJ/kg and the density of diesel is 850 kg/m^3 (RWEDP, 2004; Murphy et al. 2004). Using these data, the price of diesel can be estimated as US$ 447.06 /tonne.

The cost function equation of diesel generator plant, developed in Chapter 6 was based on the free on board price of the plant. Freight, installation, training and commissioning costs need to be added to estimate the total capital investment cost. Stassen (1995) reported the value of US$ 117/kW$_e$ and US$ 72/ kW$_e$ (1990 value) as freight and installation costs for 30 kW_e and 100 kW_e sized diesel generator plant respectively. This indicates that as the capacity of the plant increases, per unit cost of the freight decreases. No correlation was found to calculate the freight and installation costs for varying plant sizes. Most of the plant sizes considered in this study are in the scale of 300-500 kW_e. Assuming a little variation for this range of plants, an average cost of US$ 50/ kW_e has been used in this study as freight and installation cost. Stassen (1995) estimated a total fixed cost of US$ 1000 (1990 value) as training and commissioning cost of a diesel generator plant. A similar cost figure, which is equivalent to US$ 1445, in September 2004, has been used in this study as training and commissioning cost of the diesel generator plant.

8.4.2 Dual-fuel Operation

The value of the diesel replacement factor (rf) is very important. In the case of the existing diesel generators, diesel replacement is possible up to 80% (TERIIN, 2004). Value of rf affects the thermal efficiency of the engine. Tripathi et al. (1997) and Kapur et al. (1996) assumed the value as 0.70 for the economical analysis of 3 – 500 KW_e dual-fuelled (diesel and producer gas) electricity generation plant. So, in this study, the same value of 0.70 has been assumed for economical analysis of the dual-fuelled generator. Equation 7.10 and 7.11 (see Chapter 7) has been used to calculate the diesel and biomass fuel consumptions, respectively.

8.5 Default Values – Financial and Technical

Information of the plant life of the different types of biomass electricity conversion technology system is not available in the literature. Shukla (1998) estimated a project lifetime of 20 and 25 years for 100 kW_e and 1 MW_e biomass electricity plants, respectively. Stassen (1995) estimated the plant lifetime of 10 and 7 years for 10-100 kW_e capacity diesel and producer gas (or dual-fuelled) based plant respectively. Whereas, Kartha and Larson (2000) estimated an average lifetime of 25 years for small-to-medium sized biomass electricity plants. By reviewing these data, a default value of 20 years plant life has been used in this study for all types of electricity generation plants.

An average inflation rate data of 6% has been used for Bangladesh (BB, 2005a). The nominal interest rate of the nationalised bank for borrowing money for small to medium scale industry is in between 10 to 10.5% (BB, 2005b). A maximum value of 10.5% has been used in this study. The defaults values of different technical and financial parameters used in this study are summarised in Table 8.5.

8.6 Results

Sample calculation and results of the economics analysis are shown in Table 8.6 to Table 8.8. The result for any conversion technology option and for any district can be obtained by running the programme written in Matlab (see Appendices B and E)

Parameters	Unit	Conversion Technology		
		Gasification/ Anaerobic Digestion/ Direct Combustion	Diesel Generator	Dual-fuelled Generator
Plant operating hours	(hrs/day)	12.0	12.0	12.0
	(hrs/yr)	4380.0	4380.0	4380.0
No. of operators	-	3(5)[a]	2.0	3(5)[a]
Cost of repair and maintenance :as % of capital investment	(%)	3.0	3.0	3.0
Cost of operation	(US$/capita/yr)	1000.0	1000.0	1000.0
Life of plant	(yrs)	20.0	20.0	20.0
Nominal interest rate	(%/yr)	10.5	10.5	10.5
Inflation rate	(%/yr)	6.0	6.0	6.0
Others fixed costs : as % of capital investment	(%)	1.0	1.0	1.0

[a] bracketed figure is for anaerobic digestion-based plant only

Table 8.5 Default values (technical and financial) used for different types of electricity generation technologies

8.6.1 Gasification-based Biomass Electricity Plant

Table 8.6 shows the result of the economical analysis for gasification based spark-ignition engine-generator systems. Khagrachari, Dhaka and Feni districts have been selected for group A, group B and group C types of biomass resources (see Figure 8.3) respectively. The reasons for selecting these districts have been discussed in Chapter 7. In Bangladesh, the tariff of the grid electricity varies with the amount of consumption. The higher the consumption, the higher is the tariff and vice versa. The average tariff of the grid electricity supplied by the REB to the residential customer is US$ 0.0563/kWh (Islam, 2002). In non-electrified area of the country where there is no existing grid connection, Islam (2002) estimated the average tariff as US$ 0.0763/kWh and US$ 0.08475/kWh for small-grid and off-grid electricity generation respectively.

Parameter	Unit	Value		
		Group A	Group B	Group C
Corrected overall electrical efficiency	(%)	17.21	17.07	16.72
Corrected capacity of the plant	(kW)	829.71	563.18	186.58
Quantity of biomass consumption	(tonne/yr)	4876.67	2802.21	1304.32
Cost of capital investment	(US$/yr)	26117.16	20325.05	9944.25
Cost of operation	(US$/yr)	3000.00	3000.00	3000.00
Cost of biomass at plant gate	(US$/yr)	146300.21	56044.13	6000.00
Cost of repair and maintenance	(US$/yr)	783.51	609.75	298.33
Others fixed costs	(US$/yr)	261.17	203.25	99.44
Total cost of electricity generation	(US$/yr)	176462.05	80182.18	19342.02
Total electrical energy generated	(kWh/yr)	3634141.50	2466727.36	817241.25
Cost of electricity generation	(US$/kWh)	0.0486	0.0325	0.0237
Net Present Value	(US$)	1710952.47	1676371.34	649345.52
Simple Pay Back Period	(yr)	2.15	1.77	2.16
Profitability Index	-	5.04	6.34	5.02

Table 8.6 Plant economics: gasification-based spark-ignition engine-generator

Since, the objective of this study is to assess small to medium-scale off-grid biomass electricity plant; so a value of US$ 0.08475/kWh has been used as selling price of electricity to calculate the *NPV*, simple PBP and *PI* of the plant.

8.6.2 Diesel Generator Plant

Plant economics are shown in Table 8.7, if the diesel generators are chosen instead of gasification-based plants. The cost of electricity generation is higher than the estimated selling price (see Table 8.7 and section 7.6.1); so calculation of *NPV*, simple PBP and *PI* has not been performed in the case of diesel generator plant.

8.6.3 Dual-fuelled Generator Plant

Table 8.8 shows the economics of gasification-based dual-fuelled (diesel and producer gas) ICE-generator plants.

Parameter	Unit	Value		
		Group A	Group B	Group C
Corrected overall electrical efficiency	(%)	38.41	36.14	34.46
Corrected size of the plant	(kW)	829.71	563.18	186.58
Quantity of diesel consumption	(tonne/yr)	795.49	554.76	199.38
Cost of capital investment	(US$/yr)	8882.88	6512.92	2758.53
Cost of operation	(US$/yr)	2000.00	2000.00	2000.00
Cost of diesel at plant gate	(US$/yr)	355582.24	247975.95	89124.48
Cost of repair and maintenance	(US$/yr)	266.49	195.39	82.76
Others fixed costs	(US$/yr)	88.83	65.13	27.59
Total cost of electricity generation	(US$/yr)	366820.43	256749.38	93993.35
Total electrical energy generated	(kWh/yr)	3634141.50	2466727.36	817241.25
Cost of electricity generation	(US$/kWh)	0.1009	0.1041	0.1150

Table 8.7 Plant economics: diesel generators

Parameters	Unit	Value		
		Group A	Group B	Group C
Corrected overall electrical efficiency	(%)	23.32	21.68	20.47
Corrected capacity of the plant	(kW)	829.71	563.18	186.58
Diesel replacement factor	(%)	70	70	70
Quantity of biomass consumption	(kg/kWh)	0.6931	0.6014	0.9123
Quantity of diesel consumption	(kg/kWh)	0.0657	0.0675	0.0732
Cost of capital investment	(US$/yr)	19451.06	15437.04	7986.94
Cost of operation	(US$/yr)	3000.00	3000.00	3000.00
Cost of biomass and diesel at plant gate	(US$/yr)	182242.88	104061.92	30166.91
Cost of repair and maintenance	(US$/yr)	583.53	463.11	239.61
Others fixed costs	(US$/yr)	194.51	154.37	79.87
Total cost of electricity generation	(US$/yr)	205471.98	113835.35	41473.33
Total electrical energy generated	(kWh/yr)	3634141.50	2466727.36	817241.25
Cost of electricity generation	(US$/kWh)	0.0565	0.0461	0.0507
Net Present Value	(US$)	1333593.32	1238613.00	361462.80
Simple Pay Back Period	(yr)	2.07	1.81	2.90
Profitability Index	-	5.27	6.17	3.48

Table 8.8 Plant economics: dual fuelled generator

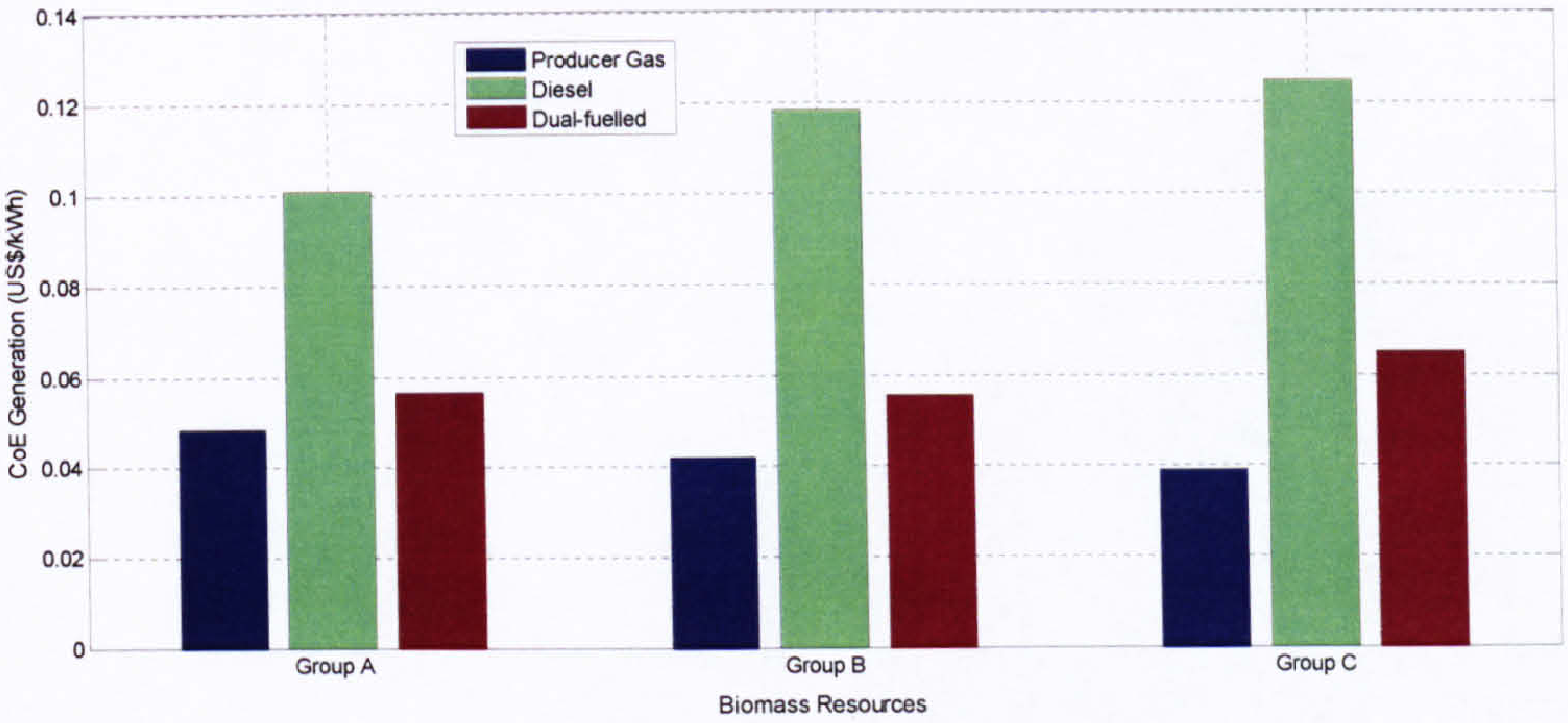
8.6.4 Conclusions

Result of the sample economical analysis shows that the cost of the pure gasification based electricity generation is lower than the other two options (i.e. diesel and dual-fuelled) for each types of biomass option. The cost of the pure gasification-based electricity generation is lower than the average tariff of electricity supplied by REB in the country (see section 8.6.1). On the other hand, the cost of electricity generation by the diesel generator is highest and also above the estimated selling price of the electricity (sees section 8.6.1). So, based on the cost of the electricity generation, pure gasification and duel-fuelled ICE-engine generator is far better than the electricity generation by diesel generator. Result also shows that NPV, PBP and PI vary significantly with technology and types of biomass resources. The NPV is highest for pure gasification based electricity generation utilising group A type of biomass resources; whereas it is lowest for dual-fuelled electricity generation utilising group C type of biomass resources. Amongst all options of gasification based ICE-generator plants, the PBP is lowest in the case of pure gasification based generator, utilising group B type of biomass resources. PI of the dual-fuelled electricity generation is higher than the pure gasification based electricity generation for group A type of biomass resources. But, in the case of group B and group C types of biomass resources, PI is higher for pure gasification-based electricity generation.

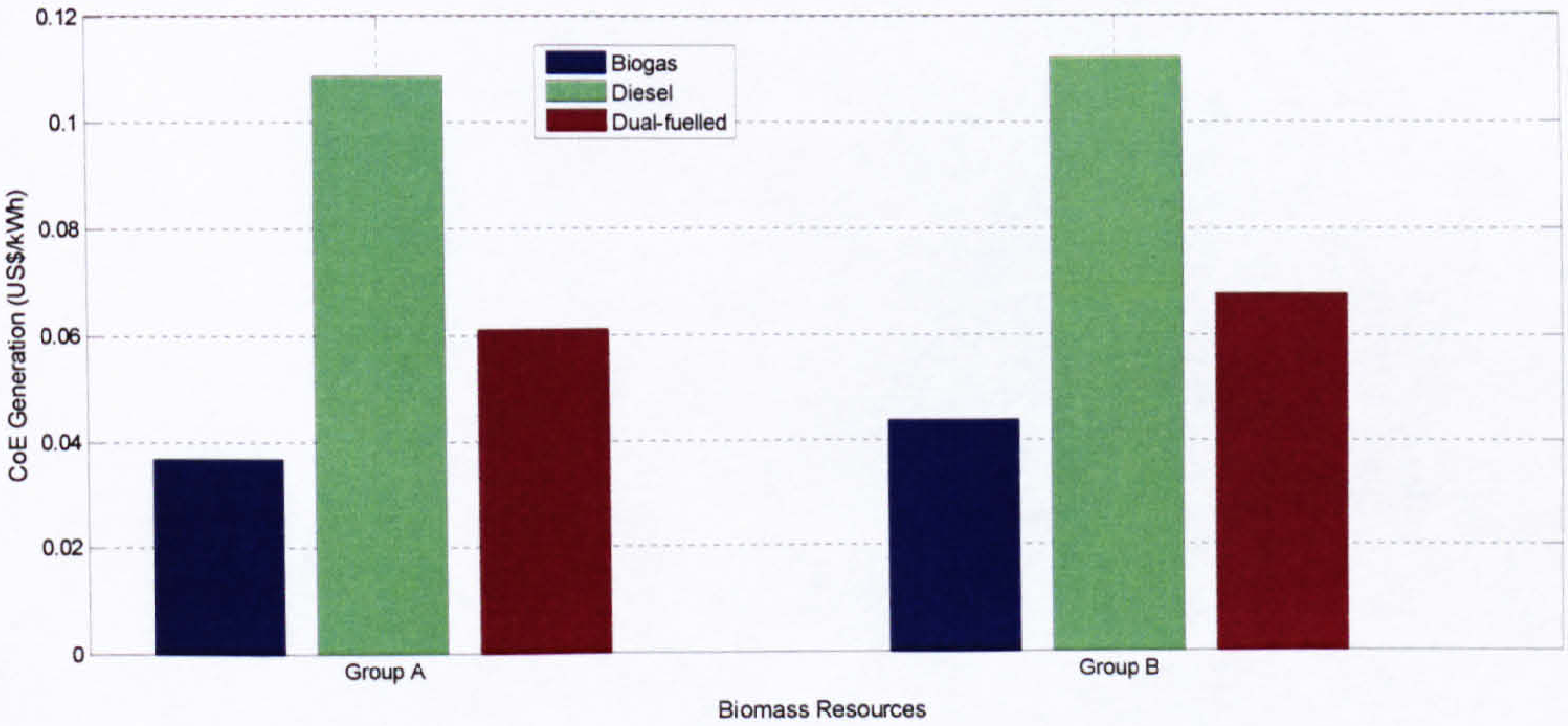
To compare the economics of the different types of electricity generation technologies, results of the economical parameters are shown in Figure 8.4 to Figure 8.6. All the available biomass resources in Khagrachari district were used to calculate the plant economics. Results shows that, of all the feasible technologies, CoE generation of the anaerobic digestion-based biomass electricity plant, using biogas, generated from animal waste and poultry waste as a fuel, is the lowest (see Figure 8.4). On the other hand, CoE generation of the direct combustion-based biomass electricity plant, using MSW fuel, is the highest, amongst all feasible technologies (see Figure 8.4). Moreover, it is estimated that CoE generation of direct combustion-based biomass electricity plant is higher than the corresponding CoE generation of the diesel generator plant (see Figure 8.4). Simple PBP, PI and NPV were not calculated for the direct combustion-based biomass electricity plant due to higher electricity generation cost compared to the estimated selling price in Bangladesh (see Figure 8.4 and section 8.6).

PBP is shortest for gasification-based dual-fuelled electricity generation plant, utilising group A type of biomass resources; whereas, PBP is highest for anaerobic digestion-based dual-fuelled electricity generation plant, utilising group B types of biomass resources (see Figure 8.5). On the other hand, PI is highest for gasification-based dual-fuelled electricity generation plant, utilising group A type of biomass resources; whereas, and PI is shortest for anaerobic digestion-based dual-fuelled electricity generation plant, utilising group A type of biomass resources (see Figure 8.5). Figure 8.6 show that the NPV of the producer gas fuelled electricity generation plant, utilising group A type of biomass, is the highest.

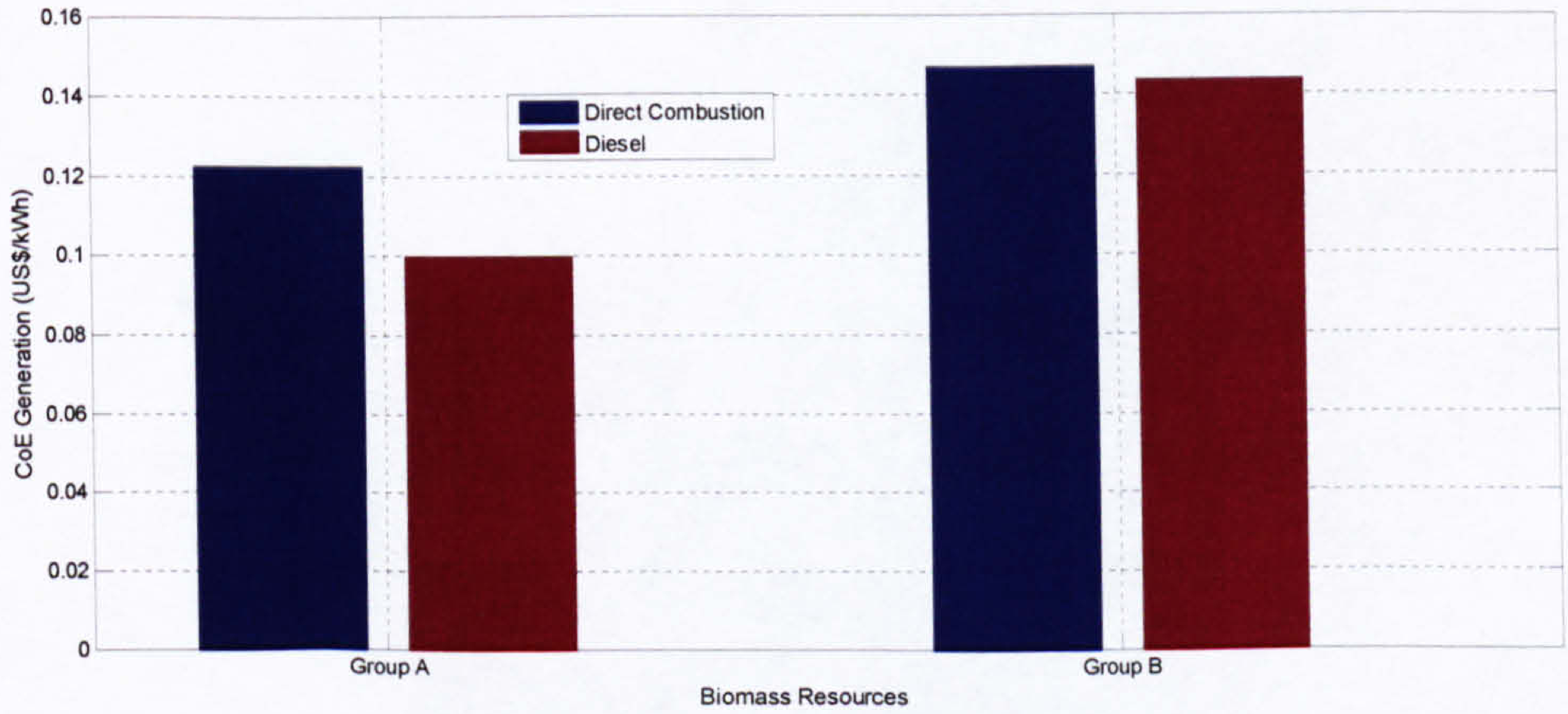
So, considering the NPV and PI value, the gasification-based duel-fuelled electricity generation plant, utilising agricultural wastes and forestry residues as fuel, is attractive amongst all options of biomass electricity plant in the Khagrachari district. On the other hand, considering the CoE generation only, the anaerobic digestion-based electricity generation technology, utilising animal and poultry waste, is the most attractive option for the Khagrachari district.



(a) Gasification

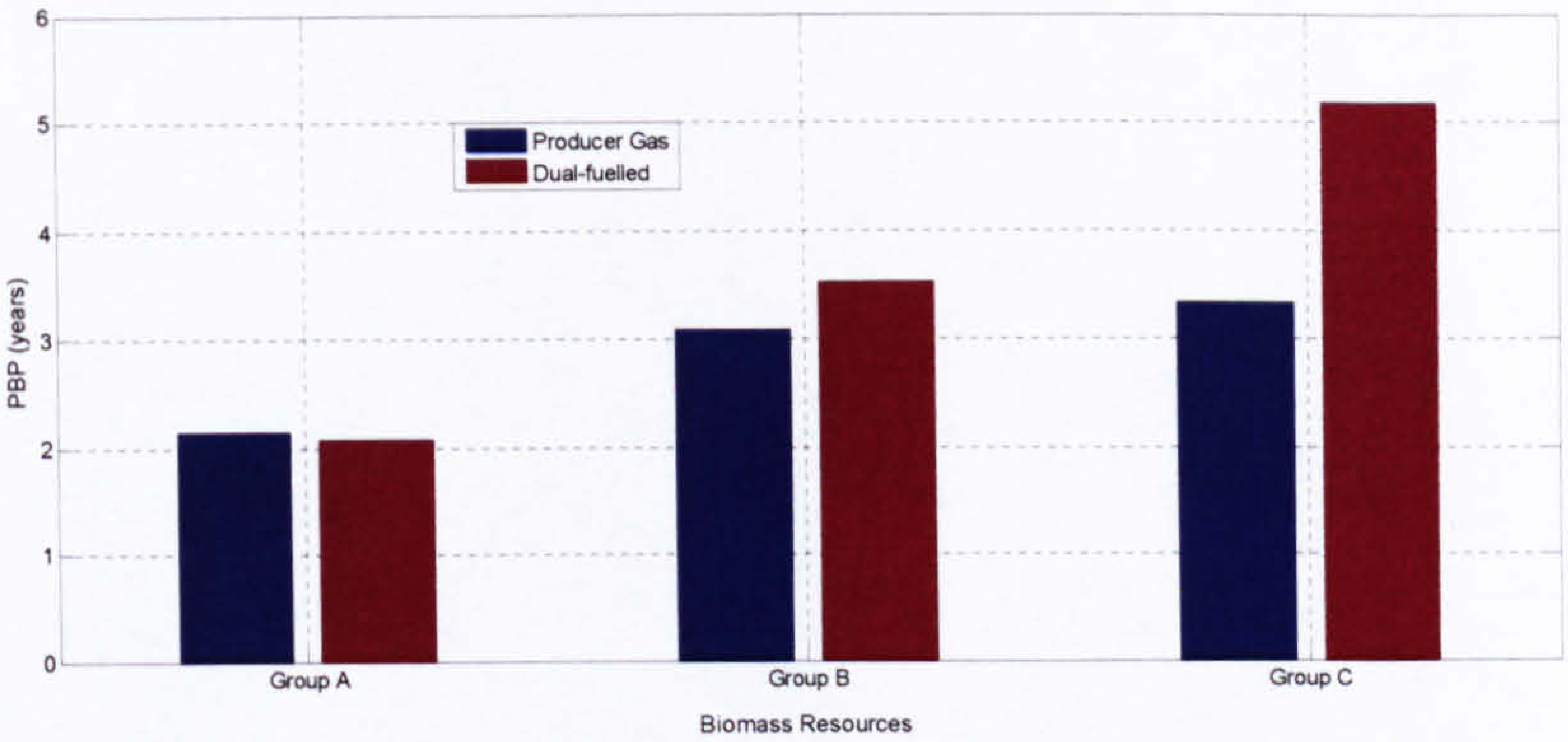


(b) Anaerobic Digestion

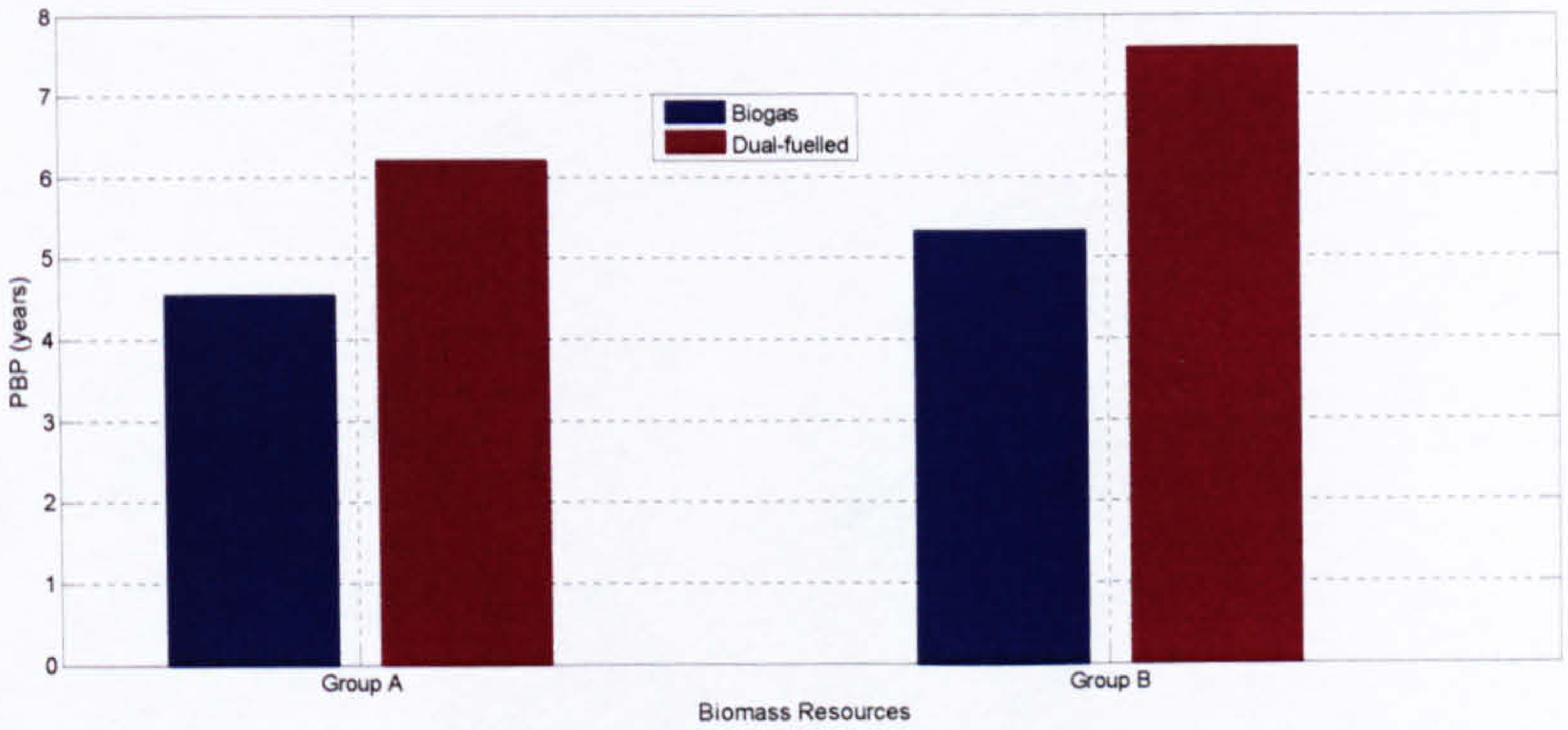


(c) Direct Combustion

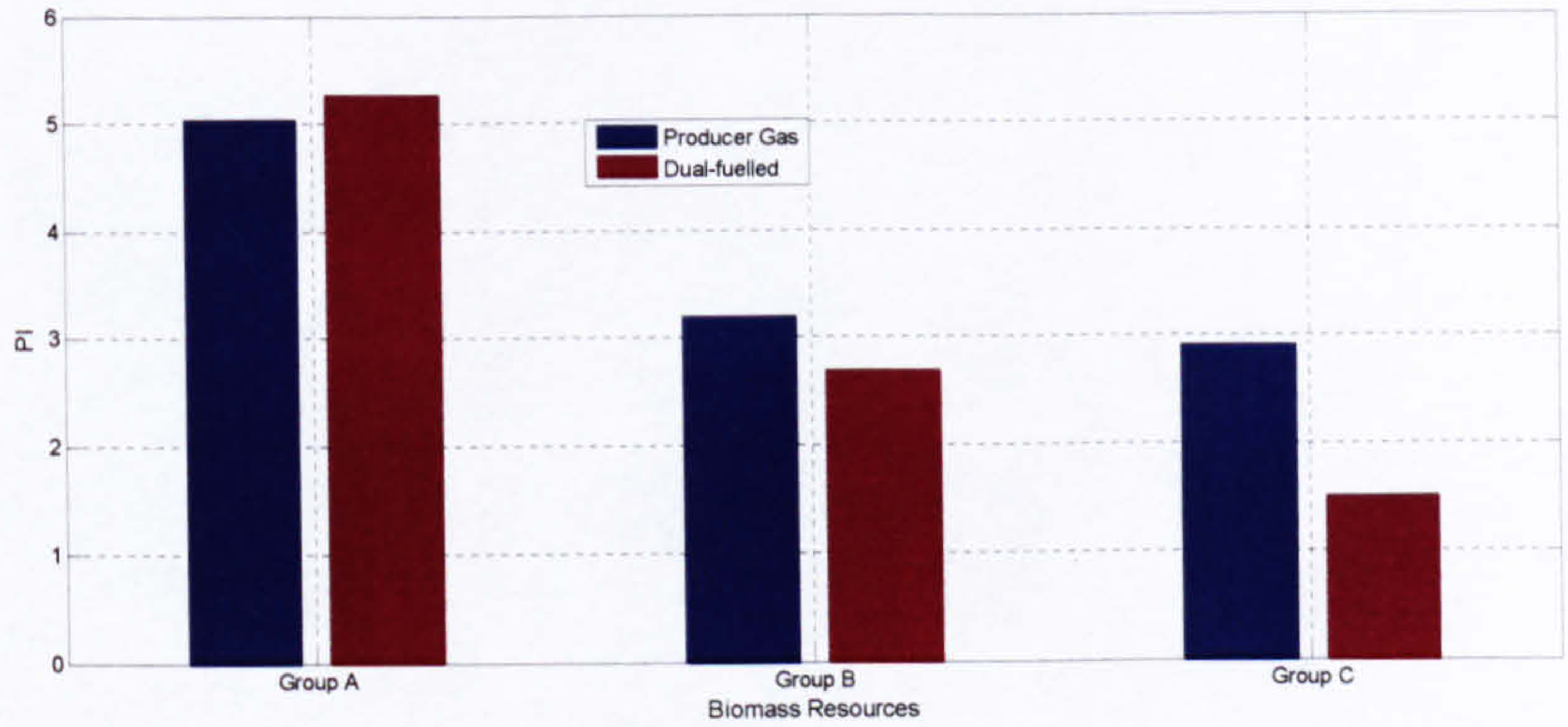
Figure 8.4 Cost of electricity generation for different types of electricity generation technologies in the Khagrachari district



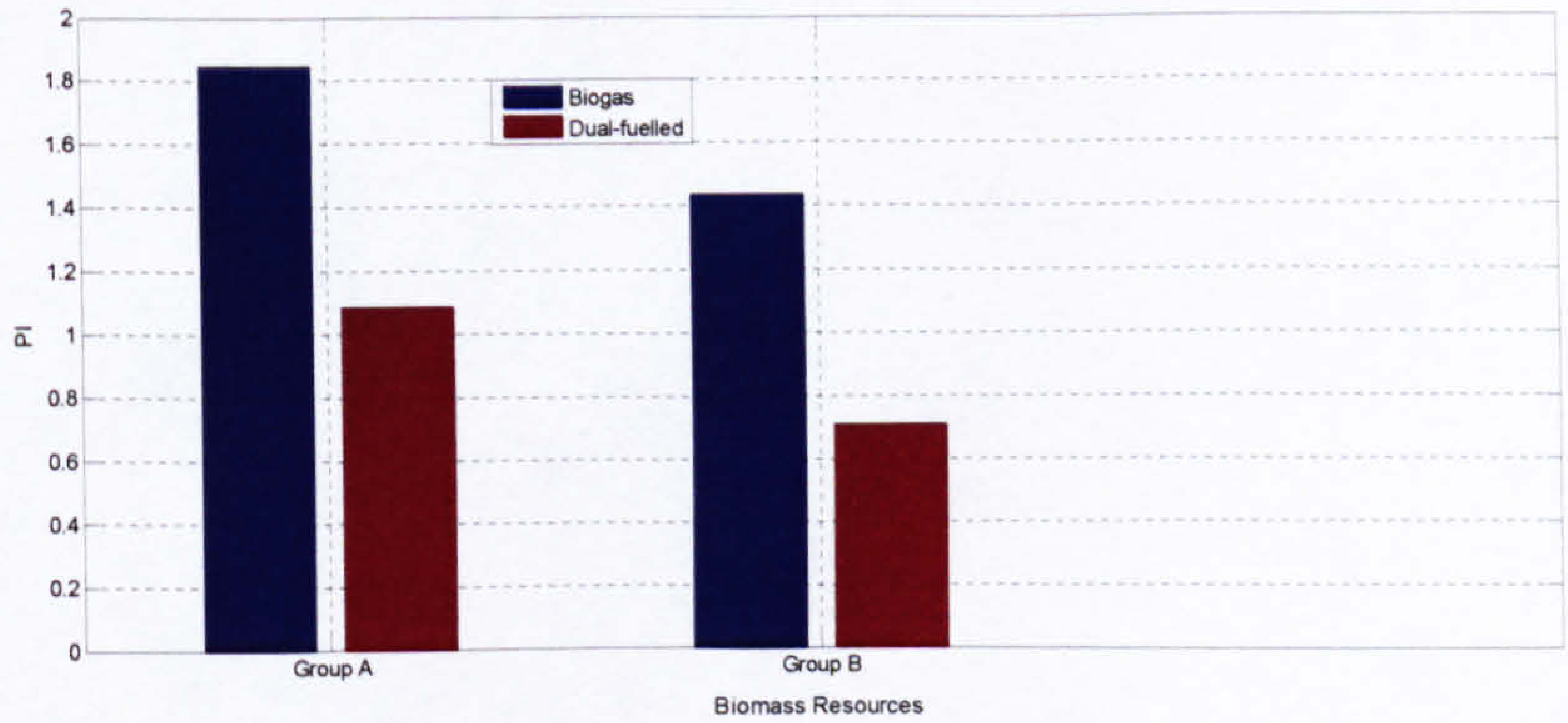
(a) PBP for Gasification



(b) PBP for Anaerobic digestion

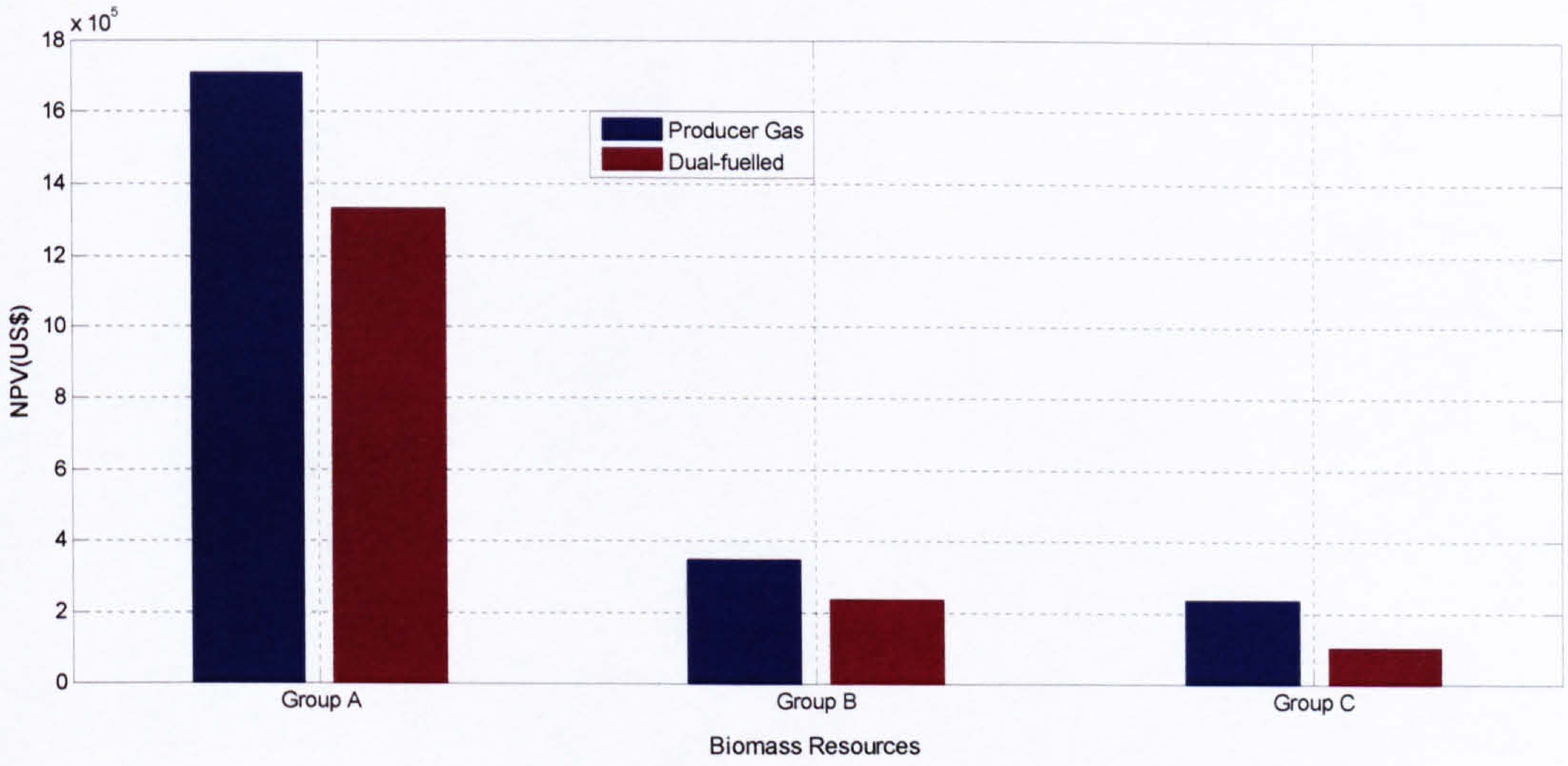


(c) PI for Gasification

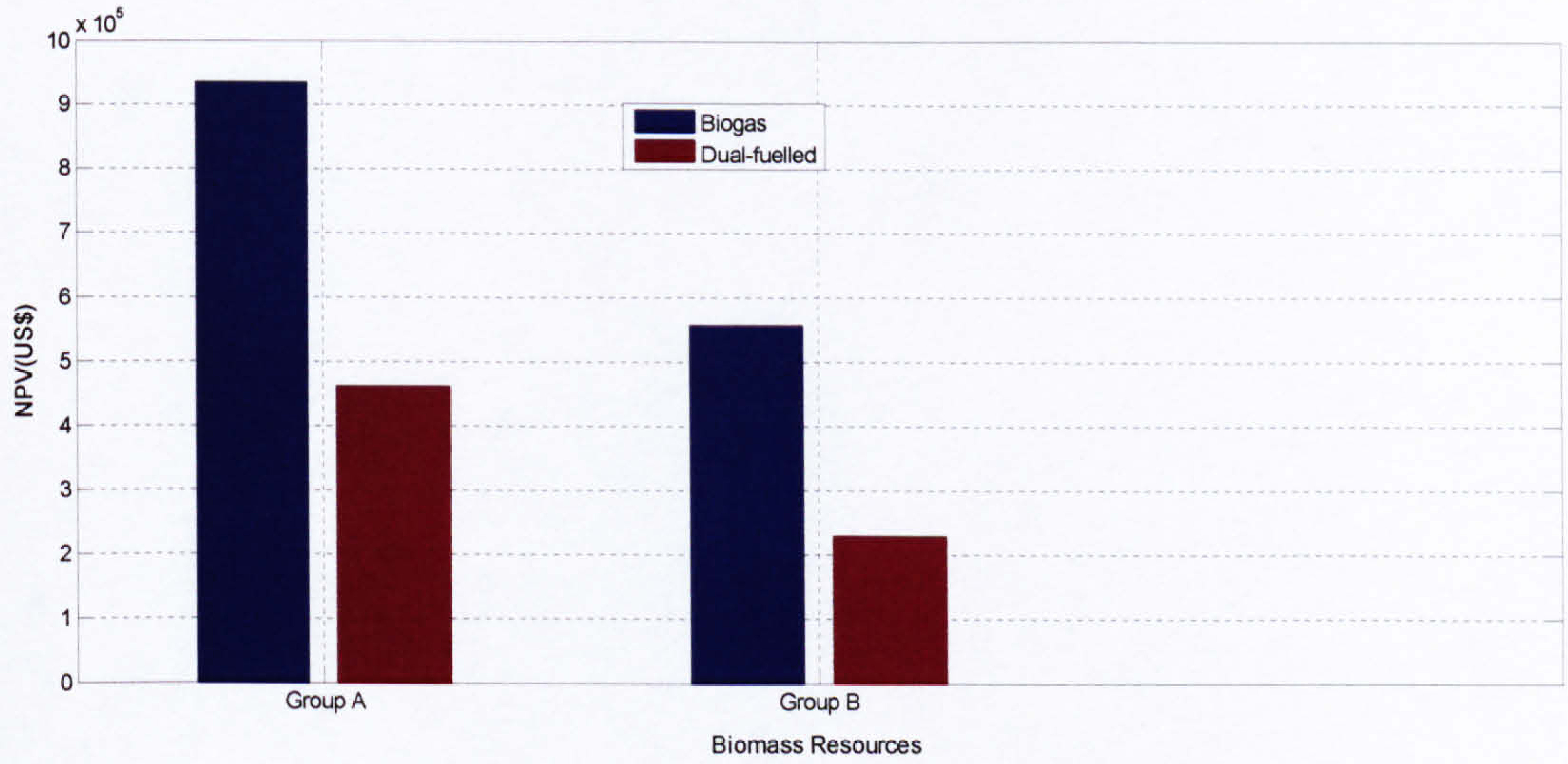


(d) PI for Anaerobic digestion

Figure 8.5 PBP and PI for different types of technologies in the Khagrachari district



(a) Gasification



(b) Anaerobic digestion

Figure 8.6 NPV for different types of electricity generation technologies in the Khagrachari district

8.7 Sensitivity Analysis

8.7.1 Introduction

Sensitivity analysis of an investment project involves the investigation of the impacts of varying the main parameters affecting the project within their expected levels. It is an important tool of cost-benefit analysis. In Bangladesh, gasification-based ICE-driven electricity generation technology shows the best option due to the combination of electricity generation potential and plant economics (see Sections 6.5.2 and 8.6). So, in this study, the sensitivity analysis has been performed only for this technology option. Impacts on the CoE and *PI* have been examined when a parameter value is changes from the default, or base, value selected.

Price of biomass has been estimated for the economic analysis. But, in real situation, price of biomass can increase or decrease. If the local demand on biomass is high and its generation is low, then the biomass price would increase. On the other hand, through the widespread of improved cooking stoves and other types of alternative resources (e.g. use of biogas for cooking, use of solar cookers) price of biomass would decrease. It is difficult to quantify exactly the extent of increase or decrease in the price of biomass. Although, a possible maximum price of biomass resources has been used as a default value (see Section 8.3.4.3), a ± 20% variation in the biomass price has been assumed to measure the impact on biomass electricity plant economics, in the context of Bangladesh. The price of diesel fuel in Bangladesh is currently very low due to the subsidy provided by the GOB. However, the GOB is considering an increase in the price of diesel, to minimise the loss in revenue of the petroleum sector (GCC, 2005). So, an increase in the diesel fuel price by between 5% and 10% has been used for sensitivity analysis.

Capital investment cost is another important parameter to consider. The GOB is giving huge subsidies to the existing electricity sector. It would be logical for the Government to provide the subsidies as a tool to encourage entrepreneurs for investing in biomass electricity sectors. It is also possible to secure aid from various international donor agencies. Accordingly, a decrease in capital investment costs of between 10% and 20% has been used for the sensitivity analysis. However, capital investment cost might also increase due to the political and economic instability of the country (or in the world). An increase of 20% has been assumed for the sensitivity analysis.

Overall energy conversion efficiency and the selling price of electricity are the two important parameters affecting plant economics. Since, the efficiency data of the plants in operation has been used to develop the correlations, a wide variation is not expected. Only ± 10% variation in efficiency has been assumed. The GOB increases the electricity tariff almost every year. On the other hand, renewable energy utilisation for electricity generation is getting popular. So it is generally expected that the capital investment cost of biomass-to-electricity technology would decrease in the future with the increase in installed capacity and electricity production. In this study, a variation of ± 10% in the selling price of electricity has been assumed.

Parameters such as plant lifetime, repair and maintenance costs, plant operating hours and nominal interest rates can also vary from the default values. Due to lack of the adequate information, it is not possible to quantify the extent of variations. So, a typical assumption of ± 20% variations of these parameters has been made in this study.

8.7.2 Results

Table 8.9 shows the impacts of the parameters considered on the CoE and PI. The sensitivity analysis has been performed for plants employing producer gas and dual-fuel (producer gas and diesel) in ICEs, utilising group A of biomass resources, in the Khagrachari district of Chittagong division. The reference (or base) values are taken from Table 8.6 and Table 8.8. The results (impacts) are compared with the reference value and expressed as a percentage change to measure the magnitude of variation from the reference values.

The results show that in both type of electricity generation plants, the impact on the cost of electricity generation (CoE) is highest due to change in biomass price. Energy conversion efficiency followed by the capital investment cost stand as the second and third most influential parameters for a producer-gas electricity-generation plant. In the case of a dual-fuelled plant, the corresponding parameters are the energy conversion efficiency, price of diesel and capital investment costs (see Table 8.9). Impacts of variations in plant lifetime, maintenance cost, operating hours and interest rates are not so important (see Table 8.9).

The variation in the selling price of the electricity shows the highest impact on the profitability index (PI) of the plant for both types of electricity generation modes. Other parameters with considerable impacts on profitability index (PI) are capital investment cost, price of biomass (plus diesel for duel-fuelled plant), plant lifetime, conversion efficiency and operating hours (see Table 8.9).

8.8 Conclusions

In this chapter, a methodology was developed to assess the biomass electricity plant economics and compare it with those of diesel and dual-fuelled electricity generation plants, in the context of Bangladesh. Economic parameters used are cost of electricity generation, simple pay back period, net present value and the profitability index.

The availability of some of agricultural-crop residues is seasonal and an average annual value has been used for the economic analysis by considering the existence of storage facilities. Correlations for capital investment costs and overall energy conversion efficiency, developed in Chapter 6, have been employed. Size of the biomass electricity plant has been calculated for maximum profitability (see Chapter 7). Computer programmes has been developed for decentralised (i.e. district-wise) biomass electricity plant economics analysis, for each types of technologies (see Appendix B).

Total cost of the electricity generation is made up of contributions from capital investment, operation, fuel, repair and maintenance and others fixed costs. Plant life has been assumed as 20 years for all types of electricity generation options considered. Investment cost has been annualised using the capital recovery factor. The costs of different types of biomass fuel have been estimated, taking into account the price of biomass at the production site and the costs of transportation, storage and pre-treatment. Some biomass resources are incurred only transportation and pre-treatment costs. The results show that the unit cost of electricity generation by gasification and

Sensitivity parameter	Increase/ Decrease	Impact on pure producer gas based ICE-generator plant				Impact on dual-fuelled ICE-generator plant (producer gas and diesel)			
		CoE		*PI*		CoE		*PI*	
		Value (US$/kWh)	% change	Value	% change	Value (US$/kWh)	% change	Value	% change
Reference/base value	-	0.0486	-	5.04	-	0.0565	-	5.27	-
Price of biomass	+20%	0.0566	16.46	3.92	-22.22	0.0607	7.43	4.49	-14.80
	-20%	0.0405	-16.67	6.16	22.22	0.0524	-7.26	6.05	14.80
Price of diesel	+5%	0.0486	0.00	5.04	0.00	0.0580	2.65	5.00	-5.12
	+10%	0.0486	0.00	5.04	0.00	0.0595	5.31	4.72	-10.44
Capital investment	-10%	0.0478	-1.65	5.71	13.29	0.0560	-0.88	5.97	13.28
	-20%	0.0471	-3.09	6.56	30.16	0.0554	-1.95	6.85	29.98
	+20%	0.0501	2.99	4.02	-20.17	0.0577	2.04	4.22	-19.94
Conversion efficiency	+10%	0.0446	-8.28	5.78	14.71	0.0540	-4.38	5.97	13.19
	-10%	0.0534	9.89	4.20	-16.62	0.0596	5.48	4.50	-14.54
Selling price of electricity	+10%	0.0486	0.00	6.22	23.32	0.0565	0.00	6.85	30.06
	-10%	0.0486	0.00	3.86	-23.47	0.0565	0.00	3.69	-30.03
Plant lifetime	+20%	0.0478	-1.65	5.73	13.69	0.0560	-0.88	5.99	13.66
	-20%	0.0497	2.26	4.21	-16.47	0.0574	1.59	4.41	-16.32
Maintenance costs	+20%	0.0486	0.00	5.03	-0.20	0.0566	0.18	5.26	-0.19
	-20%	0.0485	-0.21	5.04	0.00	0.0565	0.00	5.28	0.19
Operating hour	+20%	0.0477	-1.85	5.80	15.08	0.0567	0.35	5.85	11.01
	-20%	0.0497	2.26	4.22	-16.27	0.0565	0.00	4.62	-12.33
Nominal interest rate	+20%	0.0492	1.23	4.59	-8.93	0.0570	0.88	4.81	-8.73
	-20%	0.0480	-1.23	5.54	9.92	0.0561	-0.71	5.79	9.87

Table 8.9 Sensitivity analysis: impact on cost of electricity generation and profitability index

anaerobic digestion with an ICE-driven generator is less than the corresponding diesel-based electricity generation and the current selling price of electricity. Direct combustion technology offers the highest electricity generation potential (see Chapter 6). However, due to high capital investment cost (see Chapter 6), the cost of electricity generation is higher than the cost of electricity generation of a diesel generator with the same electricity generation capacity.

For any specific technology option, plant economics vary from one district to another; mainly due to the variation in types of biomass, biomass availability density and economic size of the plant. As a case study, the Khagrachari district was selected to study the plant economics. Amongst all options of electricity generation, cost of electricity generated from anaerobic digestion-based plant, utilising animal and poultry wastes as the feedstocks, is the lowest. On the other hand, the cost of electricity generation in a direct combustion-based plant, using MSW as a fuel, is the highest.

For gasification-based, ICE-driven, electricity-generation technology option in the Khagrachari district, PBP is lowest and PI is highest for the dual-fuelled electricity generation option. In the case of anaerobic-digestion, ICE-driven, electricity-generation option, PBP is lowest and PI is highest for biogas operated engine. Amongst all options of electricity generation, net present value is the highest for gasification-based ICE-driven generator, using producer gas generated from agricultural wastes and forestry residues. Gasification-based, dual-fuelled plant has the second highest NPV. So, considering the CoE, NPV, PBP and PI value, the gasification-based, duel-fuelled electricity generation plant, utilising agricultural wastes and forestry residues as fuel, is the most attractive in the Khagrachari district.

Sensitivity analysis has been performed to identify the parameters having the highest influence on gasification-based biomass electricity plant economics. Parameters variations from the default value have been selected considering possible scenarios in the context of Bangladesh. Impacts on the CoE and PI have been assessed for both producer gas and dual-fuel (producer gas and diesel) electricity generation options. The analysis showed that, the highest impacts on CoE occurs as a result of change in biomass price, energy conversion efficiency and capital investment cost for the case of producer gas electricity generation option. In the case of dual-fuelled electricity generation plant, changes in biomass price, conversion efficiency, diesel price and capital investment cost have the most significant impacts. Impacts on CoE due to change in values of plant lifetime, maintenance cost, operating hours, and interest rates are not significant for both types of electricity generation plants. Parameters having the highest impacts on PI are the selling price of electricity, capital investment cost, price of biomass (and diesel price for dual-fuelled plant), plant lifetime, conversion efficiency and operating hours. The sensitivity analysis proved that in case of possible worst scenario, gasification-based biomass electricity generation in Bangladesh is economically feasible.

CHAPTER 9

IMPACT ANALYSIS: ENVIRONMENTAL AND SOCIO-ECONOMIC

9.1 Environmental Impact: Introduction and Methodology

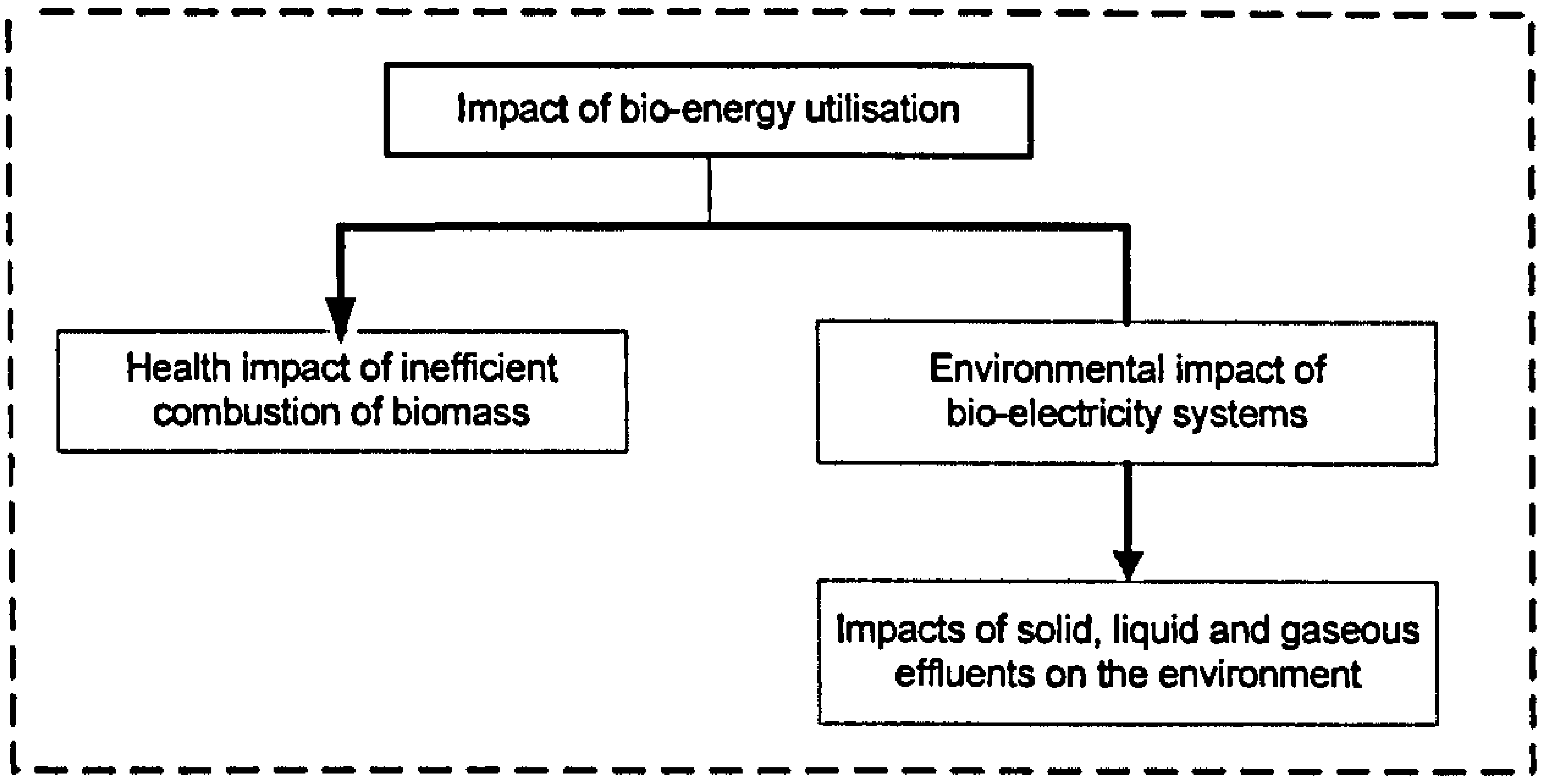
In general, renewable energy sources are considered as more environmentally favorable than many other sources. The environmental and socio-economic impacts of biomass energy systems are mainly due to the fact that such systems are land and labor intensive (Kartha and Larson, 2000). Impact assessment of biomass electricity projects may lead to the modification of proposed scenarios or development of new ones. Stages of the environmental impact assessment of a biomass energy project are (Remigio, 1997):

- Finding the expected positive and negative environmental changes.
- Measuring/understanding the scale, extent and magnitude of these environmental changes.
- Understanding whether these changes are significant from the standpoint of maintaining ecosystem integrity or not.
- The necessary steps could be under taken to minimise adverse environmental changes.
- Taking the necessary steps for informing various stakeholders (planners, decision makers, local communities, environmental NGOs) about what needs to be done as a result of the environmental impact assessment.

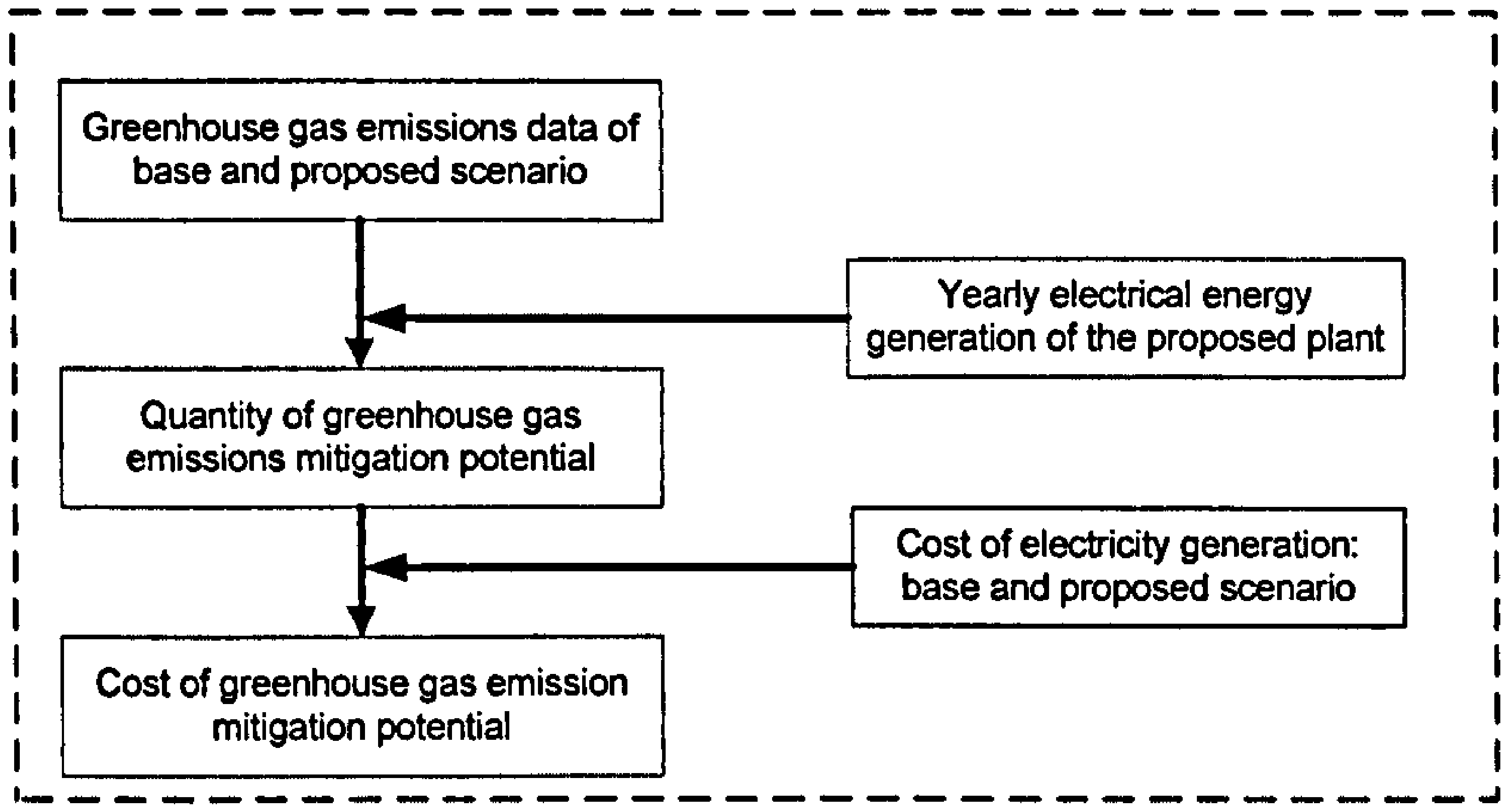
Indoor air pollution caused by the inefficient use of biomass for domestic applications poses great health risks in many developing countries. This also emits considerable amounts of atmospheric pollutants (i.e. greenhouse gases). Biomass electricity systems produce solid, liquid, and gaseous effluents. Some of these are environmentally beneficial. However, others need to be monitored and controlled to prevent any possible damage to the environment.

The main greenhouse gases are: water vapor, ozone, CO_2, CH_4, N_2O, hydro fluorocarbons (HFCs), per fluorocarbons (PFCs), and sulfur hexafluoride (SF_6). In general, biomass is CO_2 neutral, but a considerable amount of the fossil fuels is needed for the production, harvesting, transporting, and processing of biomass. In comparison with traditional power plants, biomass electricity systems can reduce greenhouse gas emissions significantly.

Figure 9.1 shows the methodology used for the environmental impact assessment. The overall efficiencies of the biomass cooking stoves used in rural area are very low. Impacts on health due to inefficient combustion of biomass and the possible interventions to reduce indoor air pollution were investigated. The impacts on environment, due to solid, liquid and gaseous effluents of a biomass electricity plant were reviewed and compared to the impacts of a fossil-fuel based power plant. The proposed and base case scenarios are biomass electricity and diesel-generator plant respectively. The amount of greenhouse gas emissions savings potential was calculated due to the employment of the biomass electricity plant instead of the diesel plant.



(a) General Impacts



(b) Greenhouse Gas Emission Mitigation Potential

Figure 9.1 Environmental Impact: Methodology

In Bangladesh, it has been proven that unit cost of electricity generation of the direct-fired biomass electricity plant is higher than the cost of electricity generated by a diesel generator (see Chapter 8). The greenhouse gas emissions potential by direct-fired biomass electricity plant was then transferred to greenhouse gas emissions mitigation costs, using the cost of electricity generation data of direct-fired biomass electricity and diesel-generator plant.

9.2 Inefficient Use of Biomass Energy

9.2.1 Indoor Air Pollution and Health Effects

More than 2 billion people in the world depend on solid fuels (biomass and coal) for their energy needs. High levels of indoor air pollution occur due to cooking with these solid fuels in traditional stoves, and this indoor air pollution is responsible for 2.7% of the global burden of diseases (WHO, 2004). Table 9.1 shows the emissions generated by different types of fuels in a typical household stove in India.

Fuel	Combustion efficiency (%)	Overall efficiency[a] (%)	Emissions (g/MJ delivered energy)				
			CO_2	CO	CH_4	TNMOC[b]	N_2O
Biogas	99.4	57.4	144	0.190	0.101	0.060	0.0017
LPG	97.7	53.6	126	0.609	0.002	0.189	0.0018
Kerosene	96.5	49.5	138	1.900	0.033	0.795	0.0008
Wood	90.1	22.8	305	11.400	1.470	3.130	0.0180
Tree root	92.9	18.9	530	13.500	2.340	3.350	0.0060
Crop residues	85.3	14.6	565	36.100	4.130	8.990	0.0280
Char fuels	84.8	14.0	710	64.000	2.370	5.600	0.0180
Dung	86.6	10.1	876	38.900	7.300	21.800	0.0220

a: Overall efficiency = Combustion efficiency * Heat transfer efficiency ; b: TNMOC: Total Non Methane Organic Compound;

Table 9.1 Emissions for major fuels used in Indian household stoves (Smith et al. 1998)

Some pollutants caused by inefficient burning of solid fuel are (Bruce et al. 2002):

- Particles (complex mixtures of chemicals as solids and liquid droplets)
- Carbon monoxide
- Nitrous oxides
- Sulphur oxides (mainly from coal)
- Formaldehyde
- Carcinogens (chemical substances known to increase the risk of cancer, such as benzo[a]pyrene and benzene)

Pollutants present in indoor smoke are responsible for respiratory diseases, low birth weight and eye problems (Pandy, 1999). Small particles of diameter less than 10 microns and in particular less than 2.5 microns are able to penetrate deep into the lungs and appear to have the greatest health damaging potential. Table 9.2 shows the different health problems caused by the indoor air pollution. The extent of the damage due to indoor pollution depends on:

- concentrations of pollutants in the indoor environment, which depends on the type of fuel and stove used, and the kitchen location
- time that individuals spend in the polluted environment

Pollutant	Potential Health Effects
Particulate matter: small particles less than 10 microns, and particularly those less than 2.5 microns aerodynamic diameter	• Wheezing, exacerbation of asthma • Respiratory infections • Chronic bronchitis and COPD[a] • Exacerbation of COPD • Excess mortality
Carbon monoxide	• Low birth weight • Increase in perinatal deaths
Benzo[a]pyrene	• Lung cancer • Cancer of mouth, nasopharynx, and larynx
Nitrogen dioxide	• Wheezing and exacerbation of asthma • Respiratory infections • Reduced lung function in children
Sulphur dioxide	• Wheezing and exacerbation of asthma • Exacerbation of COPD
Pollutant component uncertain	• Cataract

a COPD: Chronic Obstructive Pulmonary Disease

Table 9.2 Pollutants and health effects caused by the indoor air pollution (Bruce et al. 2002)

9.2.2 Interventions to Reduce Indoor Air Pollution

There are various types of interventions to reduce indoor air pollution, such as changing the fuel, using efficient combustion devices, changing or modifying the design of kitchen/living area, and changing the behaviour of the user. Some of the important interventions are:

- Use of Alternative Fuels. By using more efficient fuels (such as - biogas, producer gas, solar energy) would result in the reduction of the indoor air pollution significantly.
- Use of Improved Stoves. It has been proven that the use of improved cooking stoves increases the combustion efficiency which in turn reduces the air pollution. Examples of the improvement in efficiencies of the stoves are reported in Chapter 5.
- Improved Ventilation. Improved ventilation of the cooking and living area is another effective way of reducing exposure to pollution. Techniques available include the installation of chimneys, use of smoke hoods (with flues), eaves spaces, and installation of enlarged and repositioned windows in the kitchen. In comparison to chimney, smoke hoods have the advantage of being freestanding and independent of the stove. Effects of the improved ventilation were studied in Kenya which showed significant reduction of pollutants in indoor air pollution (ITDG, 2005):
    - Substantial reductions (80% in some homes) in particulates and carbon monoxide emission achieved by installation of smoke hoods; and
    - Emissions of particulate matters were reduced by 60%, due to enlargement of the eaves spaces in traditional houses.
- Change of behaviour. A change in user behaviour plays a big role in reducing pollution and exposure levels. Drying the biomass before use, removing the ash before starting a new fire and keeping children away from polluted areas are examples of required behavioural changes.

9.3 Environmental Impacts of Biomass Electricity

The environmental aspects of biomass energy use are diverse: from local impacts to global climate, and depends on the type and size of the technology itself. The related environmental changes due to the implementation of a biomass energy projects are:

(i) Soil Nutrients, Biodiversity and Erosion. The nutrients in the soil (i.e. phosphorous, potassium, nitrogen, calcium, magnesium, sulfur, iron, copper, chlorine, manganese, boron, zinc, and molybdenum) are taken up by plants and returned to the soil when the plants die or recycled. Unplanned utilisation of biomass resources can affect these naturally-balanced nutrient cycles. This impact on soil fertility can be reduced by establishing the maximum percentage of the recovery of agricultural residues and forestry residues. An effective way of minimising soil nutrient depletion is by allowing the most nutrient-rich parts of the plant (e.g. small branches, twigs, and leaves) to decompose in the field (Kartha and Larson, 2000). It has been estimated that in the western region of the corn belt of the USA, complete residue removal could cause a 10% decrease in crop yields and soil degradation (ABA, 2003).

Bacteria, fungi, worms, insects are the fundamental component of the soil. They help to break down the organic material and provide nutrients to plants, and they condition the soil by improving aeration and drainage. Crop residue serves a range of functions:

- control water and wind erosion;
- act as a storehouse of nutrients;
- stabilise soil structure and improves its texture;
- reduce bulk density;
- enhance infiltration and moisture retention; and
- provide energy for micro-organism activity, an essential factor in soil fertility.

Soil loss tolerances (the maximum level of soil erosion that will permit a high level of crop productivity to be sustained economically and indefinitely) vary almost from field to field, according to topography, climate, and soil type and, not least, according to the use to which the land is put. Soil erosion is already associated with many forms of intensive agriculture, and there is a danger that the removal of crop residues will hasten the destabilisation of the soil. As soil deteriorates, its ability to retain water is also affected; it become more susceptible to erosion and to drought and needs increased irrigation.

Rainfall water either infiltrates the soil or flows over the soil as surface runoff. Density of crops residues and porosity of soil determine whether to infiltrate or runoff.

(ii) Climate Change. A biomass energy system generates positive environmental impact in terms of climate change. Climate change due to the CH_4, CO_2, and N_2O is a growing concern worldwide. Capturing methane from landfills, waste water treatment, and manure lagoons prevents the methane from being vented to the atmosphere. The methane is used to generate electricity or power motor vehicles. The carbon dioxide released while burning biomass is absorbed by the next crop growing.

Release of SO_2 and NOx from the combustion causes the acid rain. Biomass has very little or no sulfur content and on the other hand co-firing of biomass is another way of reducing the sulfur emission in the atmosphere. Biomass energy utilisation also reduces the landfill pressure. Instead of land filling, biomass can utilise for power generation or for ethanol production.

(iii) Impact of Biomass Storage. The storage of harvested biomass may also pose environmental problems. Wood fuel piles may become a source of pollution if pile leach ate directly enters surface or underground waters. Also the odours may emanate from decaying biomass that has been collected and stored for future use.

(iv) Material use. Due to the conversion of dilute energy flows to useful energy flows, biomass energy systems require larger amounts of materials per unit of useful energy production compared to conventional fossil fuel systems (OECD, 1988). These materials demands impose negative environment, either due to their production process, toxicity or disposal (OECD, 1988).

9.3.1 Pollutants and Global Warming Potential

Biomass power plants generate solid, liquid, and gaseous effluents. Combustion and gasification electricity generation plant generates ash as solid waste; the amount of ash depends on the type of biomass. For gasification systems, the amount of ash varies between 1% (wood) and 20% (rice husk) by weight of the original biomass (Stassen, 1995). The ash from biomass normally contains extremely low levels of hazardous elements (EPA, 2005b). However, it should be disposed off properly.

The term Global Warming Potential (GWP) is used to compare global warming impacts of emissions of different greenhouse gases. It is defined as the ratio of radiative forcing (both direct and indirect), from one kilogram of greenhouse gas to one kilogram of CO_2 over a period of time (normally 100 years) (EPA, 2004) - see Table 9.3.

CO_2 from the biomass does not result in a net increase in atmospheric concentration because the plants absorb it during photosynthesis. It is estimated that biomass combustion contributes as much as 20-50% of global greenhouse gas emissions (Smith et al. 1998). In developing countries use of inefficient cooking stoves generate a considerable amount of non CO_2 GHG gases. Carbon emissions from biomass fuel account for more than 50% of the total carbon emissions in most developing countries in Asia. This figure ranges from 54% in Pakistan to 95% in Nepal, in the case of South Asia (see Table 9.4). If the GWP is used as an indicator of contributions to the global warming effect, biomass energy accounts around 60% of the total GWP in these countries (see Table 9.4). CH_4 is very effective greenhouse gas.

GHG	Atmospheric Lifetime (Years)	GWP[a]
CO_2	50 - 200	1
CH_4	12 ± 3	21
N_2O	120	310
HFC-23	1.5 - 264	140 - 11,700
CF_4	50,000	6,500
C_2F_6	10,000	9,200
C_4F_{10}	2,600	7,000
C_6F_{14}	3,200	7,400
SF_6	3,200	23,900

[a] 100 year time horizon.

Table 9.3 Global warming potentials and atmospheric lifetime (EPA, 2005a)

Country	Fuel	GHG emission (ktonne of C)	Total GWP	
			Ktonne of C	% of country
Bangladesh	Bio fuels	13283	16042	76
	Fossil fuels	5040	5184	24
Bhutan	Bio fuels	442	461	94
	Fossil fuels	27	28	6
India	Bio fuels	187047	225029	57
	Fossil fuels	159600	166699	43
Nepal	Bio fuels	5237	5433	95
	Fossil fuels	272	312	5
Pakistan	Bio fuels	18628	22829	54
	Fossil fuels	18178	19524	46
Sri Lanka	Bio fuels	3209	3136	70
	Fossil fuels	1118	1353	30
Region total	Bio fuels	230605	272929	59
	Fossil fuels	184235	193100	41

Note: Assuming that 60% of all biomass fuels come from sustainable supply.

Table 9.4 GWP of energy use in South Asia (except Maldives) in 1990 (RWEDP and UNEP, 2000)

Global warming causes sea level rise to which Bangladesh is most vulnerable. Figure 9.2 shows a three dimensional view of the country with the coastline and major rivers and the impacts of potential future sea level rise at 1.5 meters. This scenario was estimated in 1989. At the present expected rates of sea level rise, this stage will occur in about 150 years (UNEP, 2005).

Biomass plants emit CO_2, N_2O, and SO_2 as gaseous wastes. Compared to fossil-fuel systems, one of the big advantages of a biomass gasification plant is that it produces no SO_2 (Castro, 1999). Biomass plants offer the benefit of reducing NOx, SO_2, and CO_2 emissions (see Table 9.5).

In the case of updraft and open core gasifier systems, large amount of liquid waste (tar and particulates) is produced if wet gas cleaning systems are used. Liquid effluents can lead to contaminate local drinking water and killing of fish. Liquid effluent would be significantly less in the case of downdraft and cross draft gasification plant with dry gas clean up systems (Stassen, 1995).

In the case of anaerobic digestion plant, as the slurry remains in the digester for some days in anaerobic condition, the effluent becomes pathogen free and the outputs are smell-free combustible gas and a high-quality organic fertilizer. Table 9.6 highlights some of the environmental impacts (both positive and negative) of the feasible biomass electricity technologies.

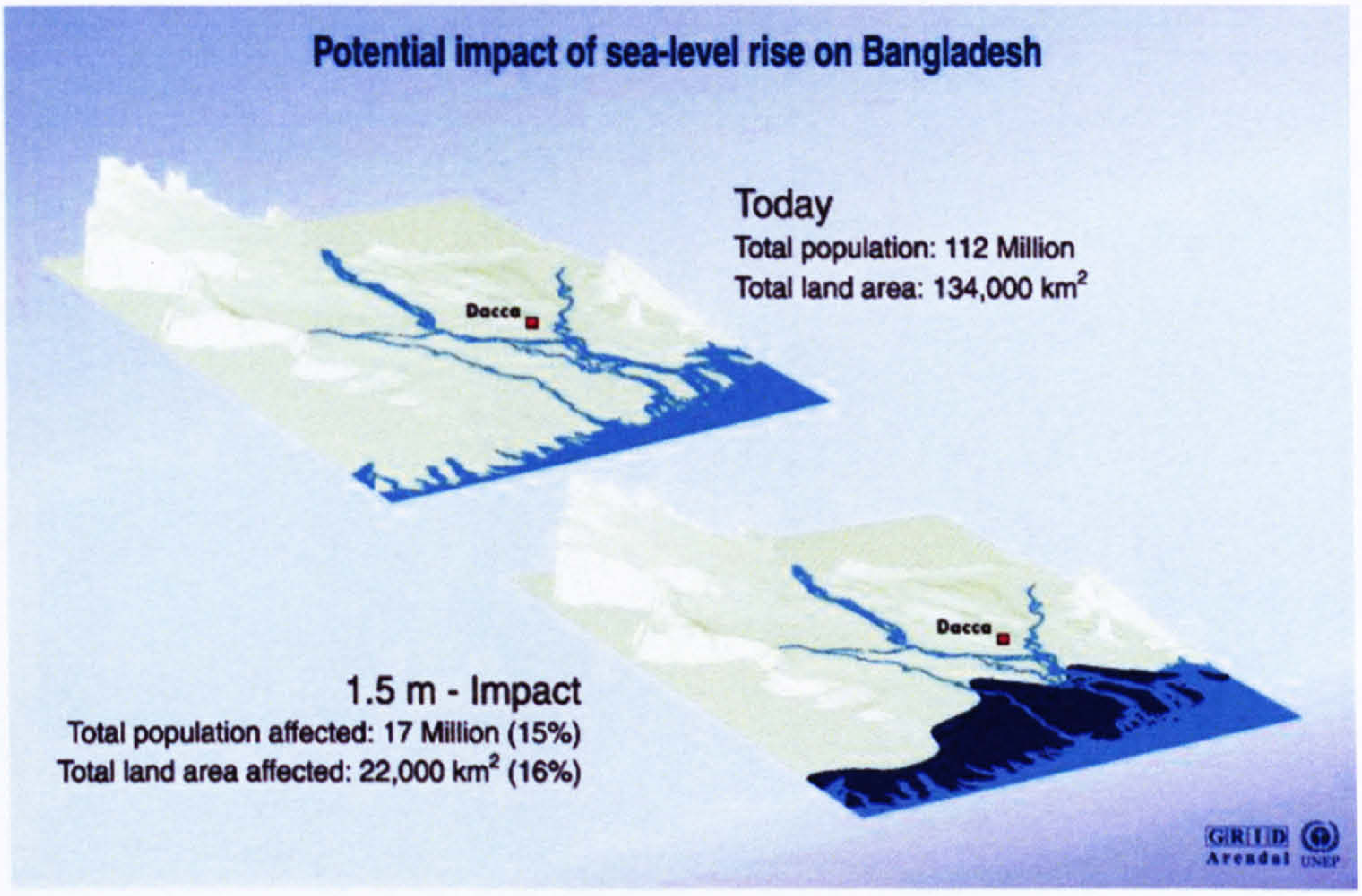


Figure 9.2 Impact of sea level rise in Bangladesh (UNEP, 2005)

Technology and fuel		Emissions (kg / MWh_e)			Comments
		SO_x	NO_x	CO	
Biomass Technology	Stoker boiler	0.036[a]	0.955[b]	5.545[b]	Based on 23 boilers in California (except SO_2).
	Fluidized bed boiler	0.036[b]	0.409[b]	0.077[b]	Based on 23 boilers in California.
	Energy crops gasification[c]	0.023	0.500-1.000	0.105	Combustor flue gas goes through scrubber before gas turbine.
Coal Technology	Stoker boiler (bituminous coal)	9.182	2.636	1.227	-
	Pulverized boiler	6.500	3.132	0.159	-
	Co-firing (50% biomass + 50% coal)	5.545	2.805	0.159	-
	Fluidized-bed boiler	1.682	1.227	4.364	-
Natural Gas Technology	Reciprocating engine	0.003	3.618[d]-17.409[d]	1.355[d] -15.909[d]	-
	Gas turbine	0.004	0.782	0.182	-
	Combined cycle gas turbine	0.002	0.414	0.027	-

a: biomass: wood residues; b: biomass not specified; c: poplar; d: depends on load and air/fuel ratio

Table 9.5 Direct air emissions of biomass and fossil fuel technology (Bain et al. 2003)

Technologies	Environmental Impacts	
	Positive	Negative / Concerns
Anaerobic Digestion	• Pathogen destruction • Less air pollution than diesel generator • No CH_4 emission, due to land filling. • Improved sanitation • Less SO_2 emissions • Effluent fertiliser value • GHG emissions savings	• Incomplete pathogen destruction • Handling safety of human excreta and animal waste • Fire hazards of biogas • Biogas leakage to atmosphere
Direct Combustion	• Wider choice of biomass utilisation • Less SO_2 emissions • GHG emissions savings	• Ash disposal problem • Emission of particulate matter • Fire hazards
Gasification	• Very low SO_2 production • GHG emissions savings	• Ash disposal problem • Waste water treatment • CO leakage

Table 9.6 Impacts of the feasible conversion technologies

9.4 Greenhouse Gas Emissions Mitigation

Biomass can reduce the CO_2 levels in the atmosphere in two ways (Hall and House, 1995):

- By growing biomass to absorb CO_2 emissions from the atmosphere.
- Using the biomass as an energy source substitutes for fossil fuels.

Although biomass is a renewable energy source, some amount of fossil fuel is used for biomass production, harvesting, transportation, and other various processes before feeding it to the power plant. Fossil fuel is needed by farm machinery, irrigation pumps, harvesting equipment, transport truck/tractor, processing equipment, and waste disposal equipment. The amount of fossil fuel needed varies depending on the type of biomass fuel. Energy ratio is a term used to analyse the emissions and is defined as the ratio of the biomass energy produced divided by the energy of the fossil fuel consumed. This ratio is generally higher for purpose grown crops, but low or negligible for many agricultural or forestry residues (Kartha and Larson, 2000). During calculation of the net greenhouse gas emissions, the entire life cycle systems of biomass fuel and fossil fuel systems should be considered. Figure 9.3 shows maximum and minimum greenhouse gas emissions for different types of electricity generation technologies using either fossil-fuel or renewable-energy, considering the entire upstream and down-stream energy chains of the life cycle. Biomass electricity plants shows considerable amount of greenhouse gas emissions mitigation potential compared to traditional power plants (see Figure 9.3).

It is assumed that the biomass feedstock is carbon neutral, which means that the carbon released during its combustion balances the carbon extracted by photosynthesis during its growth. GHG emissions can be calculated as tonnes of carbon dioxide equivalents (TCO_2 eq./year) or as tonnes of carbon equivalents (TC eq./year).

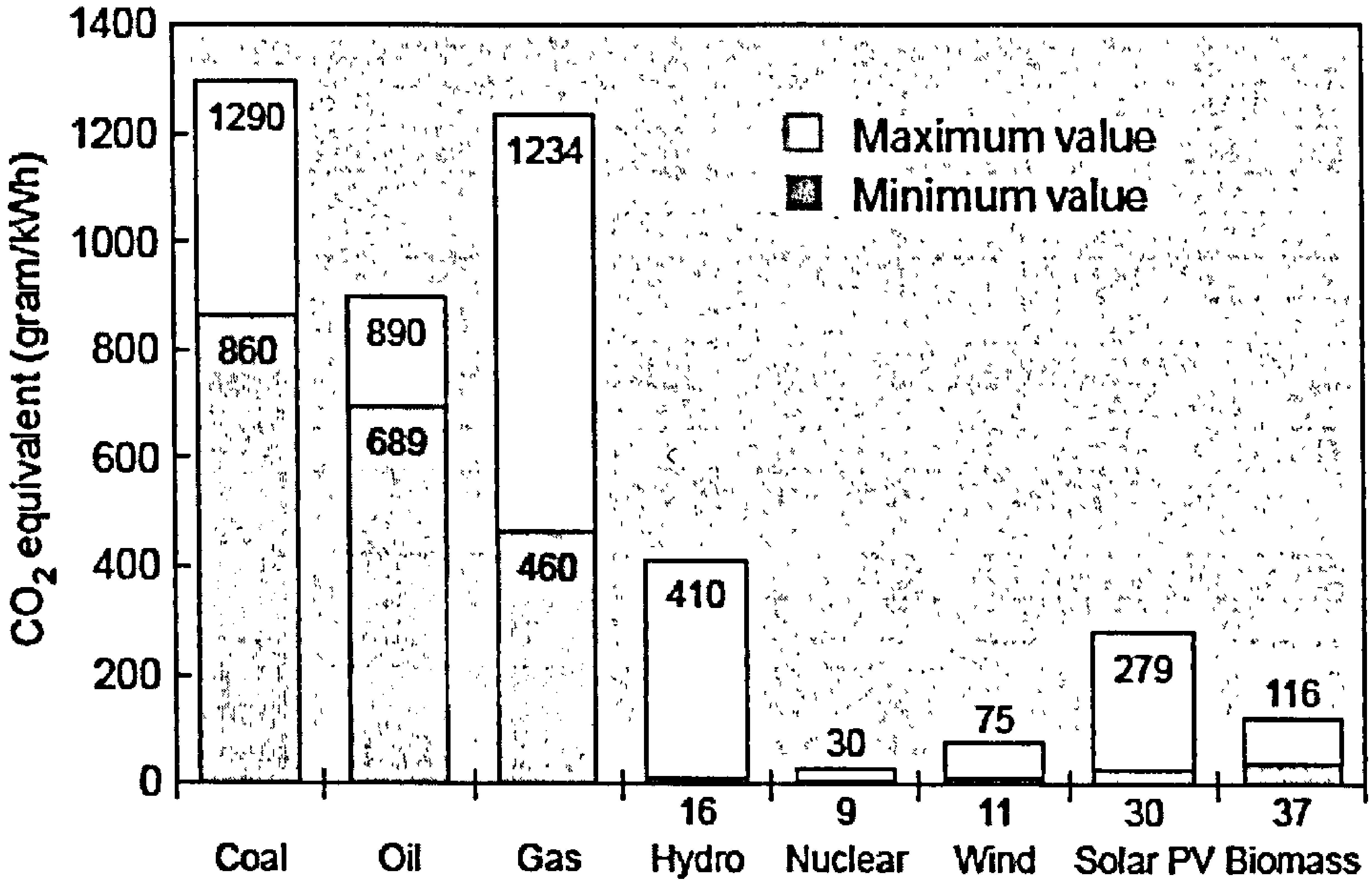


Figure 9.3 GHG emissions for full energy chain (Rogner and Khan, 1998)

GHG emission is most commonly expressed as TCO_2 eq./year, and is calculated as (Mathias and Lacrosse, 1999):

$$\text{GHG Emission in } CO_2 \text{ Equivalent} = CO_2 \text{ Emission} + CH_4 \text{ Emission} \times \text{GWP of } CH_4 + N_2O \text{ Emission} \times \text{GWP of } N_2O$$

Greenhouse gas emissions mainly depend on: type of technology, type of fuel and efficiency of conversion technology. Table 9.7 shows the greenhouse gas emissions of the different types of electricity generation systems.

9.5 Greenhouse Gas Emissions Mitigation Potential: Case Study

Diesel generator has been used as a reference technology to estimate the green house gas savings potential. Biomass electricity technologies considered are: gasification, anaerobic digestion and direct combustion. Yearly greenhouse gas emission mitigation potential was calculated using the published CO_2 eq. emissions data of diesel and biomass electricity generation technologies.

Experimental results of the greenhouse gas data were not available for a wide range of efficiency and fuel choice. Greenhouse gas emissions mitigation potential was calculated by subtracting the emission of the proposed biomass electricity system from the emission of reference diesel-fuelled electricity generation system.

Electricity generation technology[a]		Conversion efficiency (%)	Total GHG emission (TCO_2 eq./MWh_e)	References
Biomass electricity plant	Biomass gasifier and gas turbine (12%)	45.0	0.060	Kartha and Larson (2000)
	Biogas digester and diesel generator (with 15% diesel)	20.0	0. 220	Kartha and Larson (2000)
	Biomass direct combustion and steam cycle (12%)	33.0	0.100	Kartha and Larson (2000)
	MSW gasification (15%)	27.2	0.115	Murphy and McKeogh (2004)
	MSW incineration (15%)	15.3	0.220	Murphy and McKeogh (2004)
Fossil Fuel plant	Diesel generator	18.0	1.320	Kartha and Larson (2000)
		30.0	0.903	ReTScreen (2005)
	Diesel generator[b]	30.0 - 50.0	0.651	EPA (2002b)
	Coal fired combustion	22.0	1.000	Kartha and Larson (2000)
		-	0.890	Murphy et al. (2004)
		-	0.940	APPEA (2004)
	Oil fired power plants	-	0.720	Murphy et al. (2004)
	Natural gas fired engine-generator	25.0 - 45.0	0.625	EPA (2002b)
	Natural gas combined cycle	35.0	0.410	Kartha and Larson (2000)
		-	0.450	APPEA (2004)

a: bracketed figures are for biomass energy ratio; b: with catalytic converter

Table 9.7 Emission factors of the biomass and fossil fuel based electricity-generation technologies

If the cost of the biomass electricity generation is higher than cost of electricity generation of the diesel generator, then the amount of the greenhouse gas emissions saved can be expressed in terms of costs, which can be calculated as:

Cost of greenhouse gas emission mitigation (US\$/TCO_2 eq.) = [CoE of biomass electricity systems (US\$/MWh$_e$) - CoE of diesel generator systems (US\$/MWh$_e$)] / [greenhouse gas emissions avoided (TCO_2 eq./MWh$_e$)]

Electrical efficiency of the diesel generators is around 35% (see Chapter 6). So, greenhouse gas emissions of diesel generator based electricity generation (reference system) has been assumed 0.9030 TCO_2 eq./MWh$_e$, as closest available data (see Table 9.7). Greenhouse gas emissions of gasification, anaerobic digestion and direct combustion based biomass electricity generation systems have been estimated as 0.060, 0.220 and 0.100 TCO_2 eq./MWh$_e$ (see Table 9.7). As a case study, Khagrachari district has been selected for different types of electricity generation technologies, to estimate greenhouse gas emissions savings potential. Due to non-availability of data, the greenhouse gas emissions data of 0.220 TCO_2 eq./MWh$_e$ has been used for pure biogas-based electricity generation system as well. Greenhouse gas emissions savings potential has been estimated for all 64 districts – see Appendix B and Appendix E.

The default parameters (i.e. number of the operating hour, capacity of the biomass electricity plant and cost of electricity generation for both biomass electricity and diesel generator) were reported and calculated in the previous chapters of this study. In Bangladesh, cost of direct combustion based biomass electricity generation is higher than cost of electricity generation by diesel generator (see Chapter 8). So, cost of emission mitigation potential has been calculated only for the direct combustion-based technology in Bangladesh. Agricultural wastes and forestry residues have been used as biomass fuel either for gasification or direct combustion-based electricity generation technologies. On the other hand, animal wastes and poultry droppings are used for anaerobic digestion-based electricity generation technology.

Gasification-based biomass electricity plant proves maximum amount of emissions avoided followed by direct combustion and anaerobic digestion-based biomass electricity generation systems (see Table 9.8). Moreover, in Khagrachari district, gasification-based plant shows the highest greenhouse gas savings potential, compared to anaerobic digestion and direct combustion based plant (see Table 9.8). District wise greenhouse gas savings potential has been estimated for each type of feasible technology – see Appendix B. Cost of emissions mitigation of the direct combustion-based biomass electricity plant has been calculated as US\$ 27.77/ TCO_2 eq. (see Table 9.8). Mitigation cost can be used as a support to justify the installation of the direct combustion-based biomass electricity plant.

Parameter	Unit	Value		
		Gasification	Anaerobic Digestion	Direct combustion
Corrected size of the biomass electricity plant (P)	(kW)	829	343	924
Number of hours of operation (t)	(hr/year)	4380	4380	4380
Greenhouse gas emissions of reference fossil fuel technology (A)	T CO_2 eq./MWh	0.9030	0.9030	0.9030
Greenhouse gas emissions of proposed biomass electricity technology (B)	T CO_2 eq./MWh	0.0600	0.2200	0.1000
Greenhouse gas emission avoided (C) = (A – B)	T CO_2 eq./MWh	0.8430	0.6830	0.8030
Total energy generation of the plant (D) = $[(P)*(t)*10^{-3}]$	MWh/year	3631.02	1502.34	4047.12
Total greenhouse gas emissions savings (E) = (C)*(D)	T CO_2 eq./year	3060.95	1026.10	3249.84
CoE of the reference fossil fuel technology (F)	US$/kWh	0.1009	0.1086	0.1001
CoE of the proposed biomass electricity technology (G)	US$/kWh	0.0486	0.0369	0.1224
Costs of greenhouse gas emission mitigation (H) = $[(G - F)*10^3] / (C)$	US$/T$CO_2$ eq.	-	-	27.77

Table 9.8 Greenhouse gas emission mitigation and specific greenhouse gas emission mitigation costs

9.6 Socio-economic Impacts: Introduction and Methodology

The objective of the socio-economic impact studies (SIS) is to examine the local, regional and national implications of a proposed project. Social impact analysis deals with the impacts of the proposed project on employment, health, education, security, urbanisation and standard of living. And economic impact analysis means - any contribution of the proposed project for financial benefits. Impacts analysis of the proposed project on income level, business activities, agricultural production and migration are examples of economic impact analysis. Through SIS, it is possible to predict the unwanted impacts of a proposed development in time to allow these to be avoided or adjusted. SIS is not a one time task, it is repeated regularly. SIS results may be classified as primary, secondary and tertiary impacts (see Figure 9.4). These impacts are interconnected.

Both the primary and secondary impacts generate tertiary impacts independently. Creation of new business activities due to increased income is an example of tertiary impact. New business activity creates more jobs and improves the standard of living. As a result, tertiary impact adds the primary and secondary impacts. The different stages of performing socio-economic impact studies (SIS) are (Barrow, 2000):

- Scoping. This involves establishing the terms of reference, boundaries of study, and timeframe for completion/repetition of assessment, the budget, and the team. Seeking cooperation from the public to provide data is an important task in this stage.
- Problem Identification. This stage is related to the identification of the impacted social groups/stakeholders.
- Establish Alternatives. Deals with the development of the reasonable alternatives to the proposal based on the requirements of the society. Public meetings, questionnaires, and public data sources are the techniques which might be used to find out these alternatives.

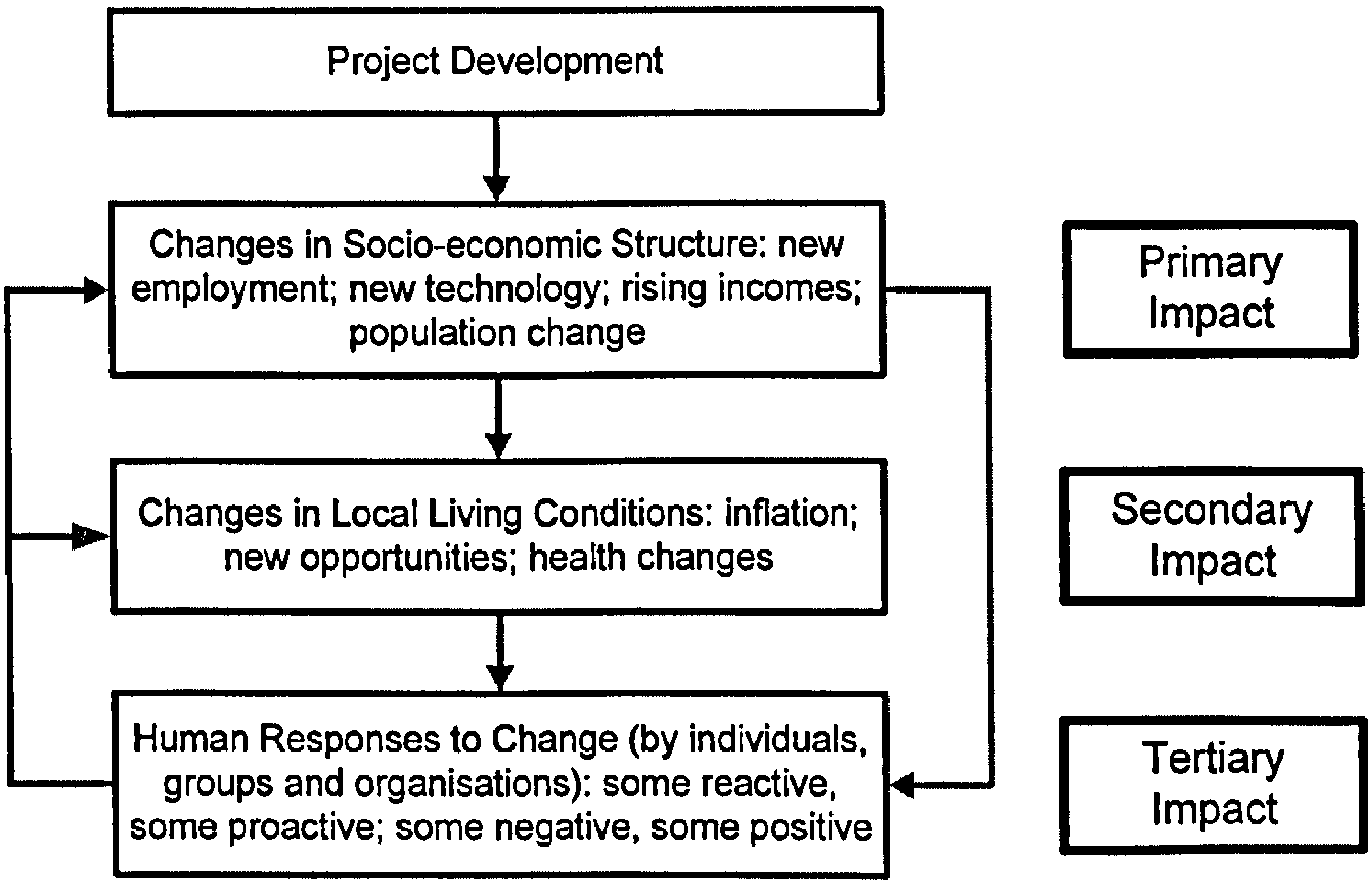


Figure 9.4 Conceptual framework of social impact studies (Barrow, 2000)

- Profiling and Projection. Determination of what is likely to be impacted and who is affected (for proposed and alternative projects).
- Assessment. Determination of the magnitude of the impacts and ranking the impacts according to importance and how people will react.
- Evaluation. Deals with rechecking the impacted group's concern and needs. In this stage, attempts are taken to establish indirect and cumulative impacts which are most likely to be effective.
- Mitigation. This stage deals with identifying the possible mitigation/adaptation. Measures to counter the unwanted impacts, which are identified.
- Management and Monitoring. The activities are: to adjust procedures and review the objectives, monitoring, decide when and how to conduct the next SIS and to check how accurate this SIS has been.

9.7 Socio-economic Benefits of Biomass Energy Activities

Local biomass energy impacts vary and depend mainly on: the technology, local economic structures and social profiles. Examples of the local economic structures are: income level and local infrastructures (e.g. number of schools, roads facilities and small industry). On the other hand, local social profile means the local employment opportunities, education, healthcare and migration attitude of the local population. Contributions of the biomass energy activities from the macro-economic point of view are (Domac et al. 2005):

- Economic growth through business expansion or employment
- Import substitution of the fossil fuel (has a direct and indirect effects on GDP)
- Efficiency improvements
- Security of energy supply and diversification.

Since electricity is considered as a basic input of modern life, providing electricity to a non-electrified area has many positive socio-economic impacts. Some of the benefits in developing countries are:

- Employment Creation. Electricity generation plant installation, operation creates direct employment. Some indirect and induced employments are also generated due to the establishment of new industries and other development activities.
- Improved Health Care. Due to the supply of the electricity, the activities in a rural clinic, such as operating refrigerators and other medical equipments, and running the operation theatre, would lead to the improved heath care services. Electricity supply would also help running clinical service for longer hours to the benefit of rural people. Due to the supply of electricity, rural people can save fossil fuels (mainly kerosene) which are used in lamps. Reduction of fossil fuel utilisation helps to reduce the indoor air emissions.
- Increased Literacy Rate. Supply of electricity helps to set up evening schools for illiterate adults who are at work during the day time. On the other hand, electricity helps to increase study habit, which has very positive effects on the future citizens of the rural population.
- Creation of Small Industries. Electricity supply helps to build small industries: agro-based or cottage industry. These industries create employment opportunity.

- Higher Standard of Living and Access to Information. Electricity supply helps households to enjoy the benefits of having necessary electrical appliances (TV, cassette player, fans, and refrigerators). Rural people can access the information quickly through TV, satellite and internet. Information about weather is very important where floods, cyclones are very common in Bangladesh.
- Urbanisation. Due to the supply of the electricity government/private organizations would come forward to invest in various development projects aimed at poverty alleviation and human development. Establishment of different development projects improves the rural infrastructures as well. Migration to cities from rural area would reduce due to employment creation and better standard of living.
- Increased Agricultural Production. Electricity supply helps to run deep-well pumps, which increases the agricultural production.
- Women's Empowerment. Provision of electricity saves time for women to do extra work (e.g. weaving and sewing projects, poultry farming and by operating small shops) after finishing their household duties, which adds to family earnings. This also reduces the health hazards due to indoor air pollution.
- Increased Time for Local Business Activity. Shops, restaurants can open for a longer hours - which helps to increase the business activities.
- Improvement of Security. Electricity helps to improve the security situation of the rural area.
- Energy Security/Self Reliance. Local community could become self reliant with respect to electricity. Use of bioelectricity would save diesel and kerosene, which would lead to the reduction of oil imports and promotion of self reliance at national level.

Employment is a function of biomass energy activities, and depends on (Domac et al. 2005): stages of the biomass energy system cycle and whether the system is labour-intensive or mechanized. Employment created by biomass energy activities are (IEA Bioenergy, 2003a):

- Direct Employment. Employment creation due to biomass production and transportation, plant construction, operation and maintenance.
- Indirect Employment. Jobs generated within the economy as a result of expenditures related to biomass fuel cycles. Indirect employment results from supporting and service industries.
- Induced Employment. Higher purchasing power due to increased earnings from direct and indirect employment may also create opportunities for secondary jobs.

Employment creation is one of the main elements for rural development. Use of biomass fuel creates more employment than using fossil fuel (see Table 9.9). Estimated employment due to biomass energy activities in some of the developing countries is shown in Table 9.10. Employment creation in biomass energy involves relatively low investment costs. Studies carried out in Brazil showed that biomass energy industries require an investment of between US$15000 and US$100000 per job generated, compared with about US$800000 per job in the petrochemical industry and over US$10 million per job for hydropower (see Table 9.11).

Type of fuel	Amount of fuel per TJ	Employment[a] per TJ of energy (person-days)
Kerosene[b]	29 klitre	10
LPG[b]	22 tonnes	10 - 20
Coal[c]	43 tonnes	20 - 40
Electricity[d]	228 MWh	80 - 110
Fuel wood[e]	62 tonnes	110 - 170
Charcoal[e]	33 tonnes	200 - 350

[a] Employment covers growing, production, extraction, transmission, maintenance, distribution and sales. It excludes employment generated outside the country for fuels that are imported.
[b] Assuming that crude oil, kerosene and LPG are imported.
[c] Varies on capital investment, energy value of the coal and the distance from demand centres.
[d] Depends on production method, conversion efficiency, transmission and distribution.
[e] Depends on the productivity of the site, efficiency of producers and distance from the market.

Table 9.9 Estimated employments by different fuel type (RWEDP, 2002b)

Country	Estimated employment (person-years)	Nature of employment
Pakistan	600,000	Whole sellers and retailers in the wood fuel trade. Involved in production, conversion and transportation. About three quarters are full time and the rest are part time.
India	3 to 4 million	-
Philippines	700,000 households (production) and 140,000 (trade)	Biomass energy production and trade.
Brazil	800,000	Ethanol industry.
	200,000	Charcoal industry.
Kenya and Cameroon	30,000	Charcoal production only.
Ivory Coast	90,000	Charcoal production only.

Table 9.10 Estimated employments in biomass energy sector in some developing countries (IEA Bioenergy, 2003a)

Area of employment creation	Investment cost required for employment creation (in 10^3 US$ / per employment)
Tree planting for electricity production	15 - 100
Ethanol production from agro based industry	12 - 22
Petrochemical industry	800
Hydropower	10000

Table 9.11 Investment cost of employment in different energy sectors: north - eastern Brazil (Carpentieri et al. 1993)

9.8 Socio-economic Impact: Evaluation and Case Study

Socio-economic aspects of biomass energy system are diverse and are particularly important for formulating and implementing programs and projects at local level. Selected assessment criteria for evaluating the socio-economic impacts of a biomass energy projects is shown in Table 9.12 in four broad categories.

Ranking and scoring the socio-economic indicators or parameters are very important to compare the socio-economic impacts of different projects. IEA Bio-energy Task 29 member countries identified some socio-economic variables and scored those variables for estimating the importance on a scale from 1-high to 10-low (see Table 9.13). The importance factors of the socio-economic parameters were estimated based on the expert's comments of the member countries (Madlener and Myles, 2000).

Category	Impact	Quantitative indicators / Assessment criterion
Basic needs	Improved access to basic services	Families with access to energy services (cooking fuel, pumped water, electric lighting, milling, etc.), quality, reliability, accessibility and cost.
Income generating opportunities	Creation or displacement of jobs, livelihoods.	Volume of industry and small-scale enterprise promoted, jobs/US$ invested, jobs/m^2 used, salaries, seasonality, accessibility to local laborers, local recycling of revenue (though wages, local expenditures, taxes), development of markets for local farm and non-farm products.
Gender or woman's participation	Impacts on labor, power, access to resources.	Relative access to outputs of biomass energy project. Decision making responsibility both within and outside of biomass energy project. Access to resources relating to biomass energy activities.
Land use competition and land tenure	Changing patterns of land ownership. Altered access to common land resources. Emerging local and macroeconomic competition with other land uses.	Recent ownership patterns and trends (consolidation or distribution of land holdings, privatization, common enclosures, transferal of land rights/tree rights). Price effects on alternate products. Simultaneous land uses (co-production of biomass fuel, fodder and food).

Table 9.12 Selected indicators of socio-economic sustainability (Kartha and Larson, 2000)

Socio-Economic Variables	Importance Factor
Employment created	1.6
Activity created	2.3
Economic gain	2.6
Increased incomes	3.1
Return on investment	3.1
Replication potential	3.9
Avoided unemployment	2.0
Support of related industries	4.3
Education	4.6
Health	5.9
Poverty alleviation	5.0
Conventional energy displaced	3.3
Stimulation of LFA	2.9
Rural diversification	4.4
Rural depopulation	3.9
Land management	4.9
Quality of life	-

Table 9.13 Ranking of socio-economic variables (Madlener and Myles, 2000)

In this research study, no survey/field study was carried out to assess the socio-economic impacts of a biomass electricity plant. Some studies were carried in India. Socio-economic situation of the rural or remote area in India is almost identical to those is similar areas in Bangladesh. So, it is expected that the results of the socio-economic impact study of biomass electricity project found in India would almost be similar if the study is carried out in Bangladesh. The biomass electricity projects and results of the socio-economic impact studies carried out in India are:

(i) Gasification based power plant in Chottomollakhali Island of Sunderbans, West Bengal, India (Mukhopadhayah, 2004):

A 500 kW (4x125 kW) biomass gasification based power plant (set up by West Bengal Renewable Energy Development Agency, India) was installed to supply the electricity to four villages of Chottomollakhali Island and serving 225 household, commercial and industrial consumers. Households were completely dependent on kerosene and in very rare cases on solar power, whereas commercial units were dependant on power supply from privately owned few 10 kW diesel power generator sets. After the installation of the gasification plant, consumption of the kerosene and diesel fuel decreased significantly (see Table 9.14).

In post-gasifier period, commercial units as well as households benefited directly or indirectly. Some indirect benefits found were:

- Household Sector. It was observed that some of the households could afford to buy durable consumer goods (e.g. radio, T.V. and electric iron) with the savings generated due to the operation of the gasification plant (see Table 9.14). Households were aware of children's comfort and enhancement of study hours. With gasifier power available up to 11:00 PM, usual household activities like watching T.V, and other socialisation activities had increased. The households were demanding longer hours of service from the gasification plant for getting more socio-economic benefits.
- Commercial Sector. Business hours extended beyond 6:30 PM or even 7:00 PM (see Table 9.14), which was the standard closing time for the pre-gasifier period. Cheaper gasifier power had in turn increased power consumption through purchase and use of large number of lighting appliances reflected through their demand for a larger number of connected points compared with pre-gasifier scenario (see Table 9.14).

(ii) Gasification based power plant in Gosaba island of Sunderbans, West Bengal, India (Ghosh et al. (2004):

A 500 kW (5 x 100 kW) biomass gasifier based power plant was installed in Gosaba island of Sundarbans, in July 1997, for electrification of five villages with more than 10000 inhabitants. Significant amount of the fossil fuel was saved due to the implementation of the project (see Table 9.15). It was also observed that the annual growth rate of commercial establishments increased from 1.8% in 1995 –1996 to 7.2% in 1998 –1999. The total number of direct and indirect employment generation was estimated at 300. The employment includes trade, transport, and operation and maintenance of the power plant.

Sources of power	Consumer (%)			
	Commercial		Household	
Fuel use for lighting	Pre-Gasifier	Post-Gasifier	Pre-Gasifier	Post-Gasifier
Kerosene	None	None	83	None
Diesel plant	100	None	None	None
Solar	None	None	17	None
Gasifier plant	None	100	None	100

(a) Fossil fuel savings in post-gasifier regime

Consumer category	Tariff rate of gasifier power per unit of consumption (US$ in 2002)	Total monthly savings in electricity bills (US$ in 2002)
Household	0.08	1.02 – 6.14
Commercial	0.09	0.50 – 4.48
Industry	0.10	—

(b) Electricity tariff structure and monthly savings in post-gasifier regime

Savings in monthly expenditure (US$ in 2002)	Number of units reporting		% in sample	
0.02 – 1.02	9		18	
1.02 – 2.04	10		20	
2.04 – 3.07	15		30	
3.07 – 4.09	9		18	
4.09 and above	7		14	
Increase in business hours (hrs)				
Nil	1		2	
<1	6		12	
1 – 2	32		64	
>2	11		22	
Electricity Connection points (nos.)	Pre -gasifier	Post -gasifier	Pre -gasifier	Post -gasifier
1 – 4	45	12	90	24
5 –10	5	35	10	70
>10		3		6

(c) Benefits of commercial units in post-gasifier regime

Table 9.14 Socio-economic impacts of biomass electricity in Sundarbans, India (Mukhopadhayah, 2004)

Energy consumption	Before installation of the power plant			After installation of the power plant		
	Cooking	Lighting	Total	Cooking	Lighting	Total
Gross (MJ)	7163	566	7729	6583	376	6959
Effective (MJ)	893	14	907	937	32	969

Table 9.15 Per capita annual energy consumption before and after installation of the biomass power plant (Ghosh et al. 2004)

9.9 Conclusions

The inefficient use of biomass causes dangerous indoor air pollution. Indoor air pollution is responsible for 2.7% of the global burden of diseases. Promoting clean and efficient biomass technologies is an effective measure in the battle against indoor air pollution and greenhouse gas emissions.

Environmental and social impact assessments of biomass electricity projects are very important and may lead to the modification of proposed scenarios or the development of new ones. Biomass energy systems have both positive and negative impacts. The environmental impacts of biomass energy systems on soil nutrition and erosion and climate change have been discussed in this chapter. The impacts of biomass storage and material use, on the environment have also been reviewed.

Biomass electricity generation systems produce solid, liquid, and gaseous effluents. Impacts of these effluents on environment have been presented and compared with the impacts of fossil-fuel based electricity generation plants. Combustion and gasification plants generate ash as a solid waste. The amount of ash generation depends on the type of biomass used. The ash from biomass normally contains extremely low levels of hazardous elements (EPA, 2005b). Compared with fossil-fuel electricity generation plants, biomass schemes offer the benefit of reducing NO_x, SO_2, and CO_2 emissions. One of the important advantages of biomass electricity plants is the very low amount of SO_2 emissions. SO_2 emissions increase the risk of acid rain. Effluents from biogas digesters are used as fertilizer in aqua-culture, mushroom production and seeds fermentation (see Chapter 6). Digester effluent should be pathogen free and effluent treatment at an elevated temperature would help in pathogen destruction. Also, the release of biogas would add to GHG emissions, this also increases the risk of fire hazards.

Up-draft gasification systems produce tar and particulates. The use of wet gas cleaning may lead to contamination of local surface water resources. Liquid effluent would be less in the case of downdraft and cross-draft gasification plant with dry gas clean up systems.

The greenhouse gas emissions savings potential as a result of the employment of the biomass electricity plant instead of the diesel generator plant was calculated. Amongst all options of biomass electricity generation in Bangladesh, gasification technology shows the highest reduction in GHG emissions. Implementation of biomass electricity projects would reduce the use of fossil fuel for lighting, which indirectly reduces greenhouse gas emissions. Therefore, biomass electricity generation presents significant amount of environmental and health benefits in Bangladesh.

Assessment criteria for evaluating the socio-economic impacts of biomass energy projects have been reviewed in the second part of this chapter. Biomass energy systems present many socio-economic benefits. Biomass energy activities create more employment and involve relatively low investment costs per employment, compared with many fossil fuel systems. Biomass energy systems can play an important role of a country's or region's development, i.e. education, employment and economic growth through business expansion, direct and indirect effects on GDP, support of traditional industries, rural diversification, and community empowerment.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

Electricity is a pre-requisite for technological progress and economic growth. Bangladesh has been facing a power crisis for about a decade, mainly because of inadequate power generation capacity compared with demand and aging infrastructures of many existing power generation facilities. Currently, power generation in the country is almost entirely dependent on natural gas. At the current annual rate of growth of consumption of 10%, the national proven reserve of natural gas may not last more than 15-20 years (Bhuiyan et al. 2000). Electricity supply to low-load rural areas is characterised by high transmission and distribution costs and transmission losses, and subsidised pricing.

In this study, a review of the country's primary energy reserves, production and consumption; electricity generation and consumption; and renewable energy utilisation have been carried out (see Chapter 2). GOB has recognised the importance of renewable energy in its 'Energy Planning Programme' and the drafting of the 'Renewable Energy Policy' (MOEM, 2002). Solar and wind energy in Bangladesh are characterised as high investment cost, seasonal and site dependent (see Chapter 2). Biomass is a major energy source in Bangladesh, which can be used for decentralised electricity generation. Worldwide, biomass-to-electricity generation has gained importance due to employment opportunity, reduction of reliance on fossil fuels and positive environmental benefits.

This research work is aimed at developing a sustainable biomass electricity generation model, especially in rural and remote areas of Bangladesh, the first of its kind in the country. The main contributions of this research work are:

- Development of methodology to estimate the national and district wise amount of biomass availability for electricity generation in Bangladesh, and estimation of national and district wise biomass energy potential.
- Review of biomass energy models available in the literature to understand the modelling techniques used and decide the appropriate techniques needed for modelling biomass electricity in Bangladesh.
- Identification of the technically feasible biomass electricity generation technologies for small- to medium-scale electricity generation in Bangladesh.
- Development of correlations for efficiency and capital investment costs of these feasible technologies as functions of the electricity generation capacity.
- Application of the optimisation techniques to estimate the optimal area of biomass collection and plant sizes, for all types of feasible technologies.
- Development of methodology to analyse district-wise biomass electricity plant economics and comparison with diesel and dual-fuelled electricity generation plant.
- Analysis of environmental and social impacts of biomass electricity in the context of Bangladesh.

Biomass energy systems models found in the literature have been studied and grouped based on the basic energy modelling techniques (see Section 4.2.1). Madlener and Myles (2000) reviewed the biomass energy models, but did not concentrate on grouping. This study revealed that the techniques used for biomass energy modelling are of four categories: econometric, optimisation, GIS and hybrid techniques (i.e. combination of more than one technique) (see Section 4.2.1). Furthermore, it has been found that biomass electricity modelling is country or region dependent, and there is no universal tool to model the biomass electricity generation of a country. Plant size and techno-economic analysis are two main issues dealt with in most of the developed biomass electricity models (see Section 4.2.1). It has been concluded that a hybrid type model, which is a combination of optimisation and techno-econometric techniques, is needed for developing biomass electricity model for Bangladesh (see Section 4.4).

In previous studies, only estimation of national total biomass generation rates (Koopmans and Koppejan, 1997; and Koopmans, 1998) and national total generation and recovery rates (Hossain, 2001) were carried out. Not all the recoverable biomass is available for electricity generation. Biomass is utilised in the country mainly as fuel for domestic cooking, and for generating process heat in industrial and commercial activities. Estimation of the national and district wise biomass availability is important for developing sustainable biomass electricity model. Some biomass resources are seasonal (see Section 5.8). This study developed a methodology to estimate both national and district-wise biomass generation, recovery and availability rates (both annual, seasonal or monthly) for electricity generation in Bangladesh. The study indicates that in 2003, the national total annual generation and recoverable rates of biomass in Bangladesh were 148.983 and 86.276 million tonnes, respectively (see Section 5.4). Of the total recoverable amount, agricultural residues represent 48.7%, followed by a 23.9% contribution from animal wastes and poultry droppings. In energy terms, the national annual amount of the recoverable biomass is equivalent to 312.596 TWh (see Section 5.4). Considering the present national consumption of biomass, the total available biomass resources for electricity generation vary from 183.848 to 223.776 TWh (see Section 5.6.1). The results obtained show that all districts, with the exception of Dhaka, has considerable amount of available resources of animal waste, poultry waste, MSW and human excreta. Currently, not all the districts have the potential to utilise agricultural wastes and forestry residues for electricity generation. However, with the implementation of the ongoing improved stoves installation programme of the GOB and utilisation of energy efficient devices, it is expected that most districts will have a considerable amount of agricultural wastes and forestry residues available for electricity generation. In 2003, amongst all districts, Serajganj had the highest total biomass availability potential of 32.861 TWh; followed by Pabna with 29.215 TWh potential (see Section 5.6.2).

Selecting the appropriate technology is very important for biomass-based electricity generation in Bangladesh. In this work, the feasible technologies identified for Bangladesh are: gasification-based ICE-generator, anaerobic digestion-based ICE-generator, and direct combustion-based steam turbine or Stirling-engine generator (see Section 6.7). No well established correlations of capital investment costs and overall energy conversion efficiency, for the above types of feasible technologies for small to medium-scale electricity generation, are available in the literature. The general trend of the capital investment cost is that it decreases with the capacity of the plant. The overall electrical efficiency, however, increases with the capacity of the plant. This trend continues up to a certain capacity, after which the investment cost and electrical efficiency remain almost unchanged. Available published data were employed to develop correlations for the capital investment cost and overall conversion efficiency as functions of the plant capacity (see Section 6.2.5, 6.3.6, 6.4.4 and 6.6.2). These correlations have been used for the economic analysis. Electricity generation potential have been estimated for each feasible technology considered. The results indicate that, in Bangladesh, the highest amount of electricity can be generated using the direct combustion-based biomass electricity generation technology, followed by the gasification-based technology (see Section 6.5.2).

In this study, optimisation techniques have been used for estimating the biomass collection area and plant size, for each feasible technology for electricity generation (see Chapter 7). Earlier studies (Fiala et al., 1997; Kumar et al., 2003; Krukanont and Prasertsan, 2003; and Krukanont and Prasertsan, 2004) used optimisation techniques only for specific conversion technologies (i.e. direct combustion and co-generation). Equations for economic radius of biomass collection and economic size of the biomass electricity plant have been derived for maximising the profitability index of the plant (see Section 7.4.1). The economic plant size increases with the biomass availability density (see Section 7.5.3). The results obtained demonstrate that the economic plant sizes estimated match plant sizes of small- to medium-scale biomass electricity generation plants installed in the developing countries (see Section 7.5.3 and Appendices D and E).

Based on the economic size, the biomass electricity plant economics have been assessed by employing a developed systematic methodology. The estimated economic parameters were compared with those for diesel and dual-fuelled (producer gas/biogas and diesel) electricity generation plant (see Chapter 8). Average availability of the agricultural residues has been used in economical analysis by considering storage facilities. The impact of the biomass storage facilities has also been studied (see Section 5.8.2). The analysis shows that in Bangladesh, biomass electricity is economically viable for two technologies: gasification and anaerobic digestion with an ICE-driven generator (see Section 8.6.4). Although, the electricity generation potential is highest for the direct combustion technology, due to high capital investment cost, the cost of electricity generation by direct combustion of biomass is higher than the cost of electricity generation by the employment of a diesel generator with the same electricity generation capacity (see Section 8.6.4).

Biomass electricity economics vary from one district to another, mainly due to the variation in types of biomass, biomass availability density and economic size of the biomass electricity plant (see Appendices E and F). Dual-fuelled biomass electricity plant has the main advantage of switching to full diesel or full biomass operation as needed. In the case of any malfunctioning of the gasifier (or digester) or shortages of biomass, the plant can be operated in a full diesel mode of operation. As a case study, for the Khagrachari district, it has been demonstrated that cost of electricity generation is cheaper, PBP is less and PI is higher for gasification based dual-fuelled electricity generation plant compared with anaerobic digestion based dual-fuelled electricity generation plant (see Section 8.6). So, from the reliability, economical and environmental point of view, gasification-based dual-fuelled biomass electricity plant is the first choice for the Khagrachari district (see Section 8.6).

The GOB provides a considerable subsidy to the electricity-generation sector. The tariff rate of electricity is much lower than the actual cost of the electricity supplied. The estimated selling price of the electricity generated from the biomass plant is reasonable and competitive with the grid electricity (see Section 8.6.1). The use of biomass for decentralised electricity generation in Bangladesh would help in reducing this subsidy significantly. Also, utilisation of biomass fuel for electricity generation would decrease the money spent for importing the fossil fuels. Reduction in subsidy and import of fossil fuels would help to increase the GDP growth rate of the country.

Sensitivity analyses were carried out in Sections 8.7 and 8.8 to assess the impacts of possible changes in the values of a number of parameters on the CoE and PI for gasification-based biomass electricity plants. It was observed that the price of biomass and selling price of electricity has the highest impacts on the cost of electricity generation and profitability index, respectively, for both producer gas-fuelled and dual-fuelled electricity generation plant (see Section 8.7). Conversion efficiency followed by the capital investment cost stand as the second and third most influential parameters affecting the cost of electricity generation for a producer gas electricity generation plant. In the case of dual-fuelled electricity generation plant, parameters having the highest influence on the cost of electricity generation are the conversion efficiency, price of diesel and capital investment cost (see Section 8.7). Parameters having the most considerable impacts on profitability index (PI) are the capital investment cost, price of biomass (plus diesel for duel-fuelled plant), plant lifetime, conversion efficiency and operating hours (see Section 8.7). The sensitivity analysis proved that in case of possible worst scenario, gasification-based biomass electricity generation in Bangladesh is economically feasible (see section 8.7).

Promoting clean and efficient biomass technologies is an effective measure in the battle against greenhouse gas emissions. The inefficient use of biomass causes dangerous indoor air pollution in the country (see Section 9.1). Results proved that the biomass electricity plant reduces the greenhouse gas emissions significantly in comparison with diesel-based electricity generation (see Section 9.5). Of all the feasible technologies, gasification shows the highest greenhouse gas emissions savings potential (see Section 9.5). The use of biomass electricity reduces the use of fossil fuel for lighting, which indirectly reduces greenhouse gas emissions. So, implementation of biomass electricity generation would provide significant amount of environmental and health benefits in Bangladesh.

Impact analysis proved that a biomass electricity plant produces many positive social impacts, such as employment creation, increased literacy rate, improved health, energy security, higher standard of living, reduced migration and urbanisation (see Section 9.7). Supply of electricity in a non-electrified area helps to establish small-scale industries and increases agricultural production through the use of deep-well pumps driven by electricity. Increase in the agricultural production and setting up of new small-scale industries would help to increase the GDP growth rate of the country.

In Bangladesh, small- to medium-scale biomass electricity plants present a good prospect for supplying electricity economically and sustainably to rural and remote areas of the country. Biomass gasification based ICE-generator plant is recommended technology due to the high electricity generation potential and related economic and environmental advantages (see Sections 6.5.2, 8.6.4 and 9.5). A computer program have been composed for district-wise sustainable biomass electricity analysis in 2003 (see Appendix B).

GOB has no plan of connecting all the homes in remote villages and isolated areas, business centres and other establishments to grid system in the near future. Implementation of biomass electricity plant would make a significant contribution towards the achievement of the government target of total electrification of the country by the year 2020.

10.2 Recommendations for Future Work

District-wise biomass consumption rate data for Bangladesh is not available. In this study, it was assumed that the pattern of consumption in individual districts mirrors the national average rate (see Section 5.6.2). Studies are needed to investigate the district-wise biomass consumption for a more accurate estimation of the corresponding biomass availability.

GIS database of each district is essential for selecting the appropriate sites for installing the biomass electricity plants. GIS database would also help to estimate the local electricity demand. Currently, LGED is working to develop the GIS database of each district. Future studies are recommended to add GIS database in the model developed in the current work.

Biomass electricity systems generates some hazardous liquid and solid wastes, which needs close monitoring or special treatment in certain cases before landfilling or disposal. In this study, waste disposal or waste handling techniques were not discussed and so the costs related to the disposal of wastes produced by the biomass electricity systems disposal have not been considered in assessing plant economics. Future studies are needed to investigate this issue in the context of Bangladesh.

Potential renewable energy sources of the country are: biomass, solar and wind. Prospects of wind energy are good in coastal areas and in remote islands. Although their operating costs are comparatively very small, the capital investment cost of the solar and wind electricity generation is quite high compared with biomass electricity plants (CBO, 2003). However, detailed research should be carried out to estimate the potential and assess the financial viability of solar and wind electricity generation in Bangladesh.

Combination of biomass with other renewable/conventional sources such as solar PV-biomass, solar PV-biomass-wind or solar PV-biomass-diesel could be a good option for decentralised electricity generation in coastal areas and in remote islands of Bangladesh. This option depends mainly on the availability of other renewable energy sources and investment cost. One of the most promising options is PV-biomass hybrid power plant. A combined PV and biomass-based electricity plant can meet all the power needs of any load situation. Biomass electricity is financially viable, but the solar PV is still costly. The viability of hybrid electricity generation in coastal and remote areas of the country needs further investigation.

In Bangladesh, a number of mixed bodies, such as the Government, NGOs and private organisations are working in the renewable energy sector. These organisations are working independently without any collaboration or co-operation. The GOB is encouraging the private sector to install small-scale power plants. Community-based biomass electricity plant was practised successfully in India. Community support (e.g. uninterrupted biomass supply, plant security and motivation of the local people to use clean energy) is vital for successful operation of biomass electricity plants. Biomass electricity plant installation strategy and funding arrangements are two important issues for implementing a biomass electricity project. This requires a further in-depth analysis.

Significant amount of the capital investment cost could be reduced if reconditioned car engines are used as prime movers. Detailed studies are needed to assess the utilisation viability of such engines.

Overall efficiencies of the traditional biomass utilisation systems used in the country are very low. The amount of biomass that could be saved by using improved cooking stoves, furnaces and boilers, and the production of biomass briquettes are considerable. Further research is needed to develop an integrated model which addresses both the efficiency improvement of the current biomass utilisation and biomass electricity generation model for the country.

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APPENDIX A
GLOSSARY

Adiabatic Flame Temperature - It is defined as the theoretical temperature of the flue gas without any heat loss either by conduction or radiation.

Bag House - Emission control device consisting of a series of fabric filters through which flue gas is passed to remove particulate material prior to release in the atmosphere.

Bio-wastes/Bio-degradable Material - Fraction of MSW which can be degraded or converted to simpler compounds by micro-organisms.

Biochemical Oxygen Demand - An indicator of water pollution, which represents the content of bio-chemically degradable substances in a water sample.

Bottom Ash - It the major portion of the total ash produced, which falls to the bottom of the combustion chamber and are mechanically removed.

Chemical Oxygen Demand - The amount of oxygen required for the complete oxidation of an organic matter in an effluent.

Capacity Factor – It is defined as the ratio of the actual energy produced by a plant during a year to the theoretical energy produced (if it were operated at full capacity throughout the year).

Discount Factor – Co-efficient commonly used to calculate the present value of future cash flows.

Fly Ash - All solid particles (e.g. ash, charred papers, cinders and soot) that rise with the hot gases from combustion rather than falling with the bottom ash. This is the minor portion (less than 10% by mass) of the total ash produced from the combustion of a solid waste.

Hydro Fluorocarbons (HFCs) - HFCs are man-made chemicals, many of which have been developed as alternatives to ozone-depleting substances (ODS) for industrial, commercial, and consumer products. The global warming potentials of HFCs range from 140 (HFC-152a) to 11,700 (HFC-23).

Inflation - The overall general upward price movement of goods and services in an economy.

Load Factor – It is defined as the ratio of the actual energy produced by a plant during the operational period of a year to the theoretical energy produced during the same period.

Mtoe - Thermal equivalence of any fuel expressed as million tonnes of oil equivalent. 1 Mtoe = 42 PJ.

Moisture Content (MC) - There are three parts in biomass: water (w), ash (a), and dry and ash free matter (daf). MC can be expressed as:

- Wet basis: ratio of weight of water to the weight of total biomass
- Dry basis: ratio of the weight of water to the weight of ash and remaining material present in the biomass
- Dry-ash-free basis: ratio of the weight of water to the weight of dry-ash-free matter of biomass.

Nominal Interest Rate - The rate at which the borrower gets the loan from the lending organisation for investment.

Octane Rating - A measure of a gasoline's resistance to exploding too early in the engine cycle, which causes knocking. The higher the rating, the lower is the chance of premature ignition.

Pathogen - A disease causing organism.

Particulate Matter (PM) - Mixture of particles that can adversely affect human health, damage materials, and form atmospheric haze that degrades visibility. PM is usually divided into different classes based on size, ranging from total suspended matter (TSP) to PM-2. The smallest particles pose the highest human health risks.

Real Interest Rate – The real interest rate is the nominal interest rate minus the rate of inflation, and thus the interest rate is adjusted for inflation.

Sulfur Hexafluoride (SF_6) - The global warming potential of SF_6 is 23,900. SF_6 is used for: insulation and current interruption in electric power transmission and distribution equipment; in the magnesium industry to protect molten magnesium from oxidation and potentially violent burning; in semiconductor manufacturing to create circuitry patterns on silicon wafers; and as a tracer gas for leak detection.

APPENDIX B

COMPUTER PROGRAMME AND CD-ROM INSTRUCTIONS

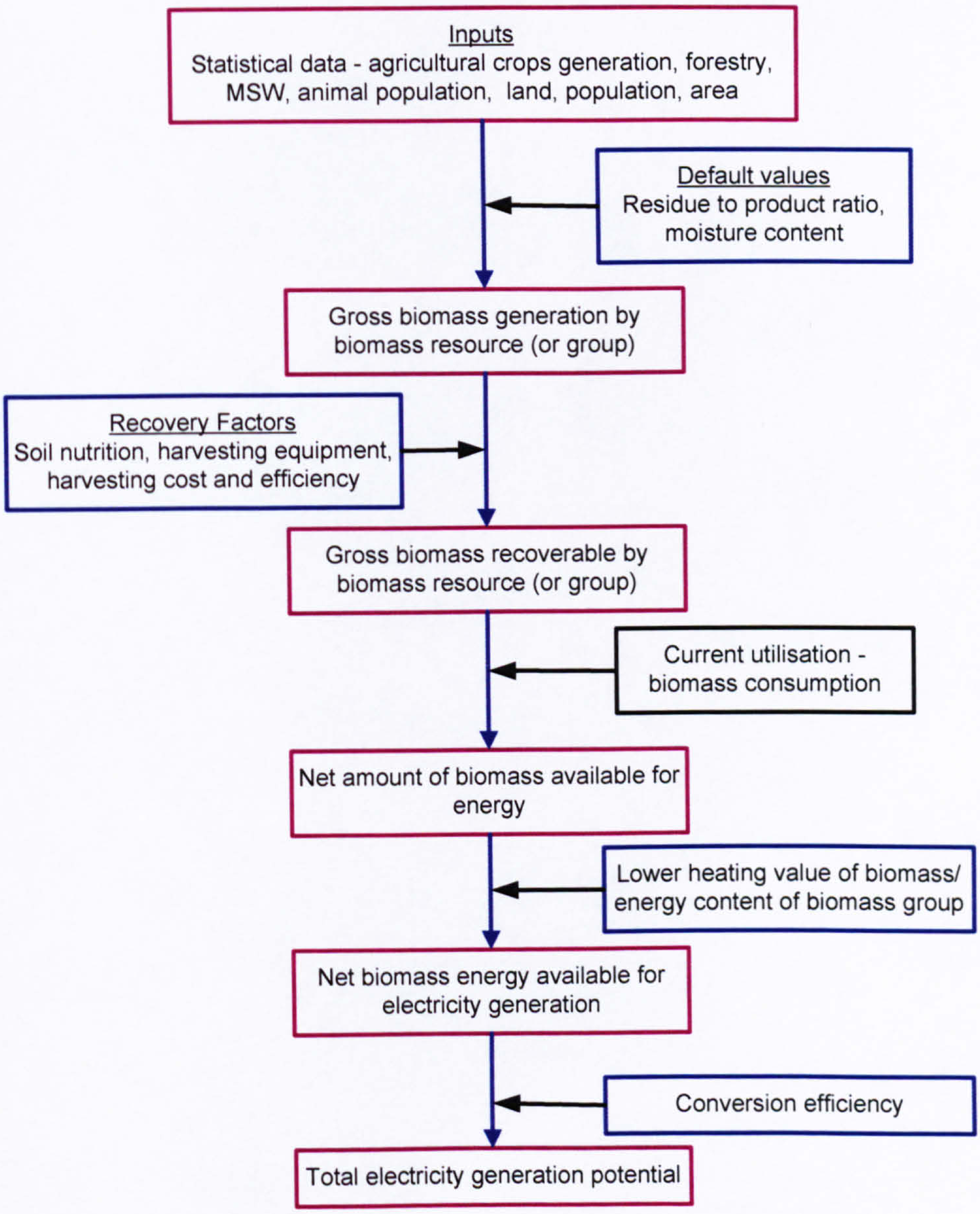

Figure B1 Flow-chart for estimation of district-wise biomass, generation, recovery and availability (by resource), and electricity generation potential

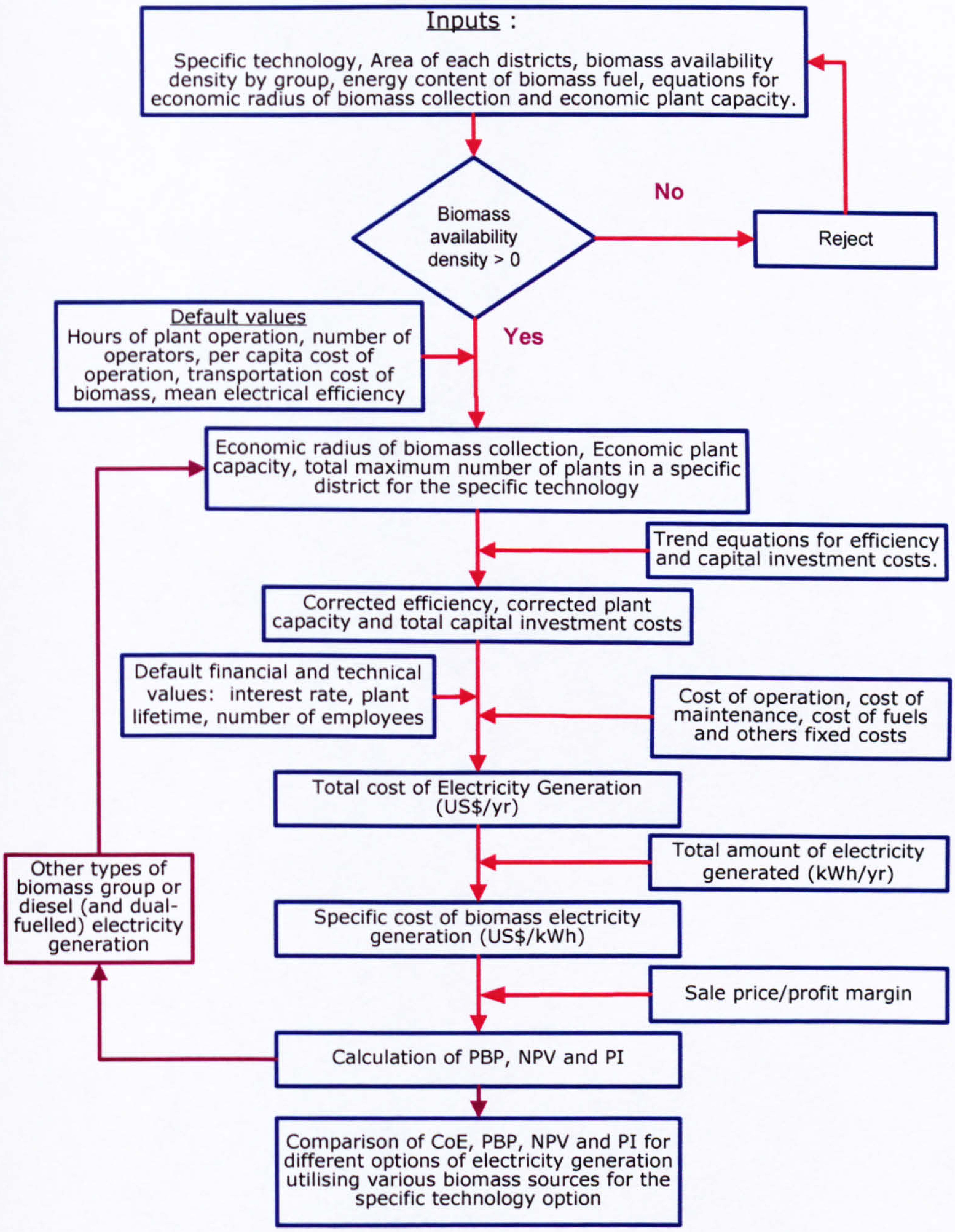

Figure B2 Flow-chart for assessment of biomass electricity plant economics and comparison with diesel and dual-fuelled electricity plant

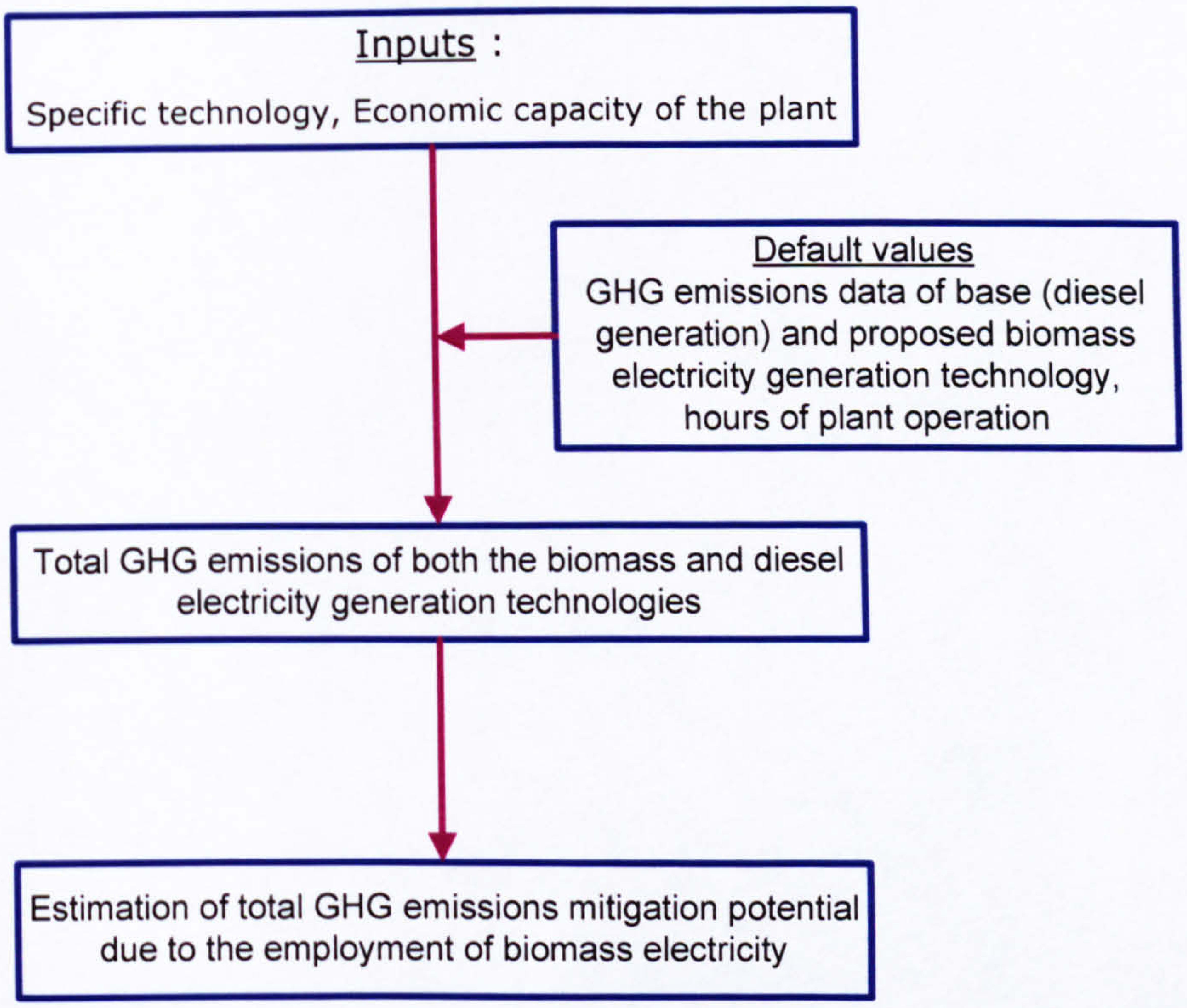

Figure B3 Flow-chart for assessing the environmental benefits of biomass electricity compared to diesel electricity generation

The necessary instructions for using the attached CD-ROM are:

- Check whether the Matlab software language is available in the computer
- Open the Matlab and insert the CD-ROM in the CD drive
- In the open dialogue box of Matlab, select the CD drive
- Open the folder
- Follow the steps shown in Figure B4
- Open (make sure that in Files of type box option 'ALL MATLAB Files' appears) and run the selected file

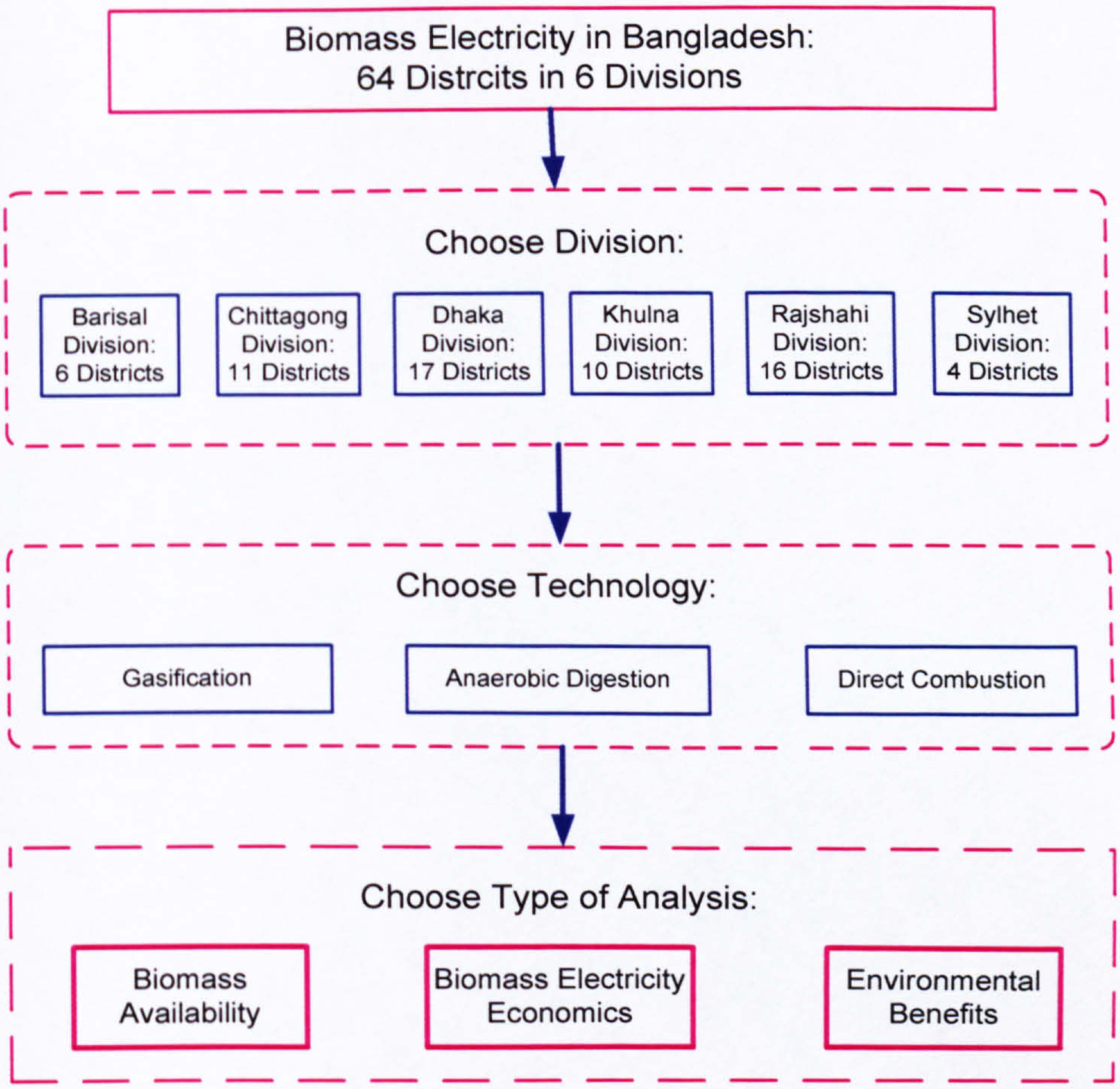

Figure B4 Biomass electricity analysis by district

APPENDIX C
BIOMASS GENERATION BY DISTRICTS

C1 Generation Rates of Agricultural Crops

Name of districts	Generation rate[a] (tonnes)											
	Rice		Wheat		Jute		Sugarcane		Pulses (total)		Vegetables (total)	
	1998	2003	1998	2003	1998	2003	1998	2003	1998	2003	1998	2003
Barguna	166866	210513	0	0	46	6	6343	3584	8171	4780	3873	2075
Barisal	31338	39535	107	86	678	95	2935	1658	3206	1875	3157	1692
Bhola	421015	531140	5279	4268	54	8	3776	2133	6482	3792	15027	8052
Jhalokhati	95432	120394	78	63	4825	675	1668	942	4352	2546	5896	3159
Patuakhali	357337	450806	0	0	317	44	3473	1962	16025	9374	9478	5078
Pirojpur	15997	20181	0	0	0	0	7832	4425	760	445	3957	2120
Banderban	28531	35994	0	0	0	0	2894	1635	287	168	4249	2277
Brahamanbaria	590124	744483	25100	20291	65463	9159	616	348	2138	1251	14268	7645
Chandpur	292758	369335	19577	15826	7588	1062	81785	46207	5957	3485	96957	51950
Chittagong	612742	773017	260	210	0	0	27705	15653	3533	2067	120866	64760
Comilla	677659	854914	30566	24710	11422	1598	13537	7648	6837	3999	879076	471012
Cox'sBazar	671670	847359	0	0	0	0	7033	3974	366	214	5319	2850
Feni	273427	344947	245	198	3	0	7190	4062	2511	1469	12671	6789
Khagrachari	587059	740616	0	0	0	0	233731	132054	2118	1239	20210	10829
Laksmipur	224324	283001	655	530	1243	174	6446	3642	3006	1758	103376	55389
Noakhali	311905	393490	143	116	136	19	3151	1780	11930	6979	44977	24099
Rangamati	57124	72066	15	12	69	10	2373	1341	294	172	18649	9992
Dhaka	189014	238454	11160	9022	17662	2471	11425	6455	44983	26313	5699	3054
Faridpur	170897	215599	67052	54206	61682	8630	612006	345773	18350	10734	29984	16066
Gazipur	376330	474767	1924	1555	6297	881	80868	45689	685	401	55059	29501
Gopalganj	202297	255212	8650	6993	4612	645	35183	19878	19542	11431	14301	7663
Jamalpur	324394	409246	28391	22952	60341	8442	280227	158323	2899	1696	3957	2120
Kishoreganj	592220	747127	19901	16088	26025	3641	56332	31827	1460	854	12857	6889
Madaripur	154380	194761	5055	4087	11598	1623	57172	32301	5744	3360	24779	13277
Manikganj	182640	230413	19731	15951	7380	1033	72751	41103	4221	2469	9457	5067
Munshiganj	92626	116854	5004	4045	8596	1203	12831	7249	1262	738	8626	4622
Mymensing	805437	1016115	19770	15982	33517	4689	4958	2801	2900	1696	50112	26850
Narayanganj	96344	121545	2525	2041	2695	377	8260	4667	463	271	36374	19489
Narsingdi	240667	303618	2174	1757	11352	1588	27394	15477	1233	721	17954	9620
Netrokona	538723	679637	7671	6201	11208	1568	4845	2737	4346	2542	212700	113965
Rajbari	138547	174787	14607	11808	31916	4465	215110	121533	5641	3300	7924	4246
Shariatpur	109550	138205	12264	9914	9856	1379	8731	4933	4601	2691	27613	14795
Sherpur	20224	25514	21682	17528	9390	1314	41469	23429	4712	2756	38215	20476

Tangail	489079	617008	42169	34090	53130	7433	190623	107699	4401	2574	37549	20119
Bageraht	261028	329305	293	237	192	27	32600	18418	6815	3986	47120	25247
Chuadanga	127370	160686	60355	48792	36283	5076	576635	325789	8150	4767	38205	20470
Jessore	530979	669867	23045	18630	74792	10464	62214	35150	85263	49875	156746	83985
Jhenaidah	418125	527494	22162	17916	41858	5856	685943	387546	13443	7864	163397	87549
Khulna	310439	391641	2282	1845	6322	885	43423	24533	4992	2920	12900	6912
Kushtia	231622	292207	40330	32603	15407	2156	309329	174765	9988	5843	12899	6911
Magura	360761	455125	9105	7361	14349	2008	181860	102748	19220	11243	34499	18485
Meherpur	103855	131020	29033	23471	17688	2475	144491	81635	8420	4925	35412	18974
Narail	68925	86954	2200	1779	5060	708	15980	9028	2927	1712	13357	7157
Satkhira	399557	504069	1390	1124	12107	1694	52395	29602	9181	5370	57135	30613
Bogra	751376	947914	25075	20271	9313	1303	18544	10477	872	510	19255	10317
Dinajpur	1995	2517	700	566	610	85	0	0	9895	5788	12195	6534
Gaibandha	445712	562297	17959	14518	28041	3923	192755	108903	7826	4578	71461	38289
Joypurhat	228869	288734	11959	9668	16441	2300	138458	78226	752	440	36016	19297
Kurigram	316927	399826	30634	24765	37766	5284	20815	11760	2251	1317	16804	9004
Lalmonirhat	542871	684870	10685	8638	17335	2425	27309	15429	706	413	8729	4677
Naogaon	6943	8759	7751	6266	6114	855	1660	938	16339	9558	188	101
Natore	217519	274416	64478	52125	27424	3837	6966	3936	10894	6373	300	161
Nawabganj	236100	297857	13915	11249	6085	851	816489	461302	4323	2529	22468	12038
Nilphamari	296339	373852	15636	12640	31310	4381	3285	1856	277	162	40191	21534
Pabna	5625417	7096859	662202	535331	4235440	592579	1557150	879762	27305	15972	35280	18903
Panchagarh	1644	2074	1029	832	348	49	1104	624	1527	893	5863	3141
Rajshahi	699564	882549	77394	62566	23452	3281	2162398	1221717	11565	6765	135001	72334
Rangpur	409498	516611	42007	33959	53188	7442	261599	147799	3359	1965	1525	817
Sirajganj	6994020	8823448	314874	254548	481470	67362	2551350	1441468	114381	66908	404868	216930
Thakurgaon	1961	2474	515	416	1392	195	16668	9417	401	235	7759	4157
Habiganj	346437	437055	2815	2276	696	97	78943	44601	118	69	15444	8275
Maulvibazar	311660	393181	92	74	0	0	2537	1433	154	90	17621	9441
Sunamganj	296448	373990	1952	1578	1214	170	6804	3844	637	373	9768	5234
Sylhet	302555	381694	529	428	0	0	654	369	2391	1399	40924	21927
Total	**30985193**	**39090000**	**1864151**	**1507000**	**5660798**	**792000**	**12103031**	**6838000**	**589788**	**345000**	**3428496**	**1837000**

[a] district wise data of actual rates of generation in 1998 was collected from BBS (2002) and generation rates of whole country in 2003 was collected from FAOSTAT (2004).

Table C1 Estimated amount of generation rates of agricultural crops by districts in 2003

C2 Forests and Forestry-industry Residue

Biomass from forests and forestry industry in 2003: 8.871 million tonnes (FAO Forestry, 2003)

Name of districts	Area under forests in 1998[a]			Forests and forestry-industry residues in 2003 (tonnes)
	(km^2)	Fraction of total forests area	Share of total forests area (%)	
Barguna	118.29	0.00653254	0.65	57950.08
Barisal	0.00	0	0.00	0.00
Bhola	214.98	0.011872225	1.19	105318.36
Jhalokhati	4.20	0.000231944	0.02	2057.57
Patuakhali	161.40	0.008913281	0.89	79069.60
Pirojpur	4.79	0.000264527	0.03	2346.61
Banderban	2591.44	0.143111729	14.31	1269542.29
Brahamanbaria	2.13	0.000117629	0.01	1043.48
Chandpur	0.00	0	0.00	0.00
Chittagong	1216.41	0.067175986	6.72	595917.30
Comilla	9.40	0.000519113	0.05	4605.04
Cox'sBazar	80.55	0.004448357	0.44	39461.32
Feni	8.46	0.000467202	0.05	4144.54
Khagrachari	1457.94	0.08051443	8.05	714242.46
Laksmipur	63.76	0.003521133	0.35	31235.92
Noakhali	350.16	0.019337512	1.93	171542.82
Rangamati	4829.59	0.266713092	26.67	2366008.37
Dhaka	0.18	9.94046E-06	0.00	88.18
Faridpur	50.72	0.002801001	0.28	24847.65
Gazipur	281.67	0.015555167	1.56	137989.68
Gopalganj	0.08	4.41798E-06	0.00	39.19
Jamalpur	19.08	0.001053689	0.11	9347.26
Kishoreganj	0.00	0	0.00	0.00

Madaripur	0.00	0	0.00	0.00
Manikganj	0.00	0	0.00	0.00
Munshiganj	0.00	0	0.00	0.00
Mymensing	156.58	0.008647098	0.86	76708.29
Narayanganj	0.40	2.20899E-05	0.00	195.96
Narsingdi	0.00	0	0.00	0.00
Netrokona	10.48	0.000578756	0.06	5134.14
Rajbari	0.00	0	0.00	0.00
Shariatpur	0.00	0	0.00	0.00
Sherpur	64.83	0.003580223	0.36	31760.11
Tangail	472.34	0.026084877	2.61	231398.61
Bageraht	1248.87	0.068968583	6.90	611819.40
Chuadanga	0.04	2.20899E-06	0.00	19.60
Jessore	0.04	2.20899E-06	0.00	19.60
Jhenaidah	0.00	0	0.00	0.00
Khulna	2600.76	0.143626424	14.36	1274108.14
Kushtia	0.11	6.07473E-06	0.00	53.89
Magura	0.06	3.31349E-06	0.00	29.39
Meherpur	0.00	0	0.00	0.00
Narail	0.04	2.20899E-06	0.00	19.60
Satkhira	1448.96	0.080018511	8.00	709843.17
Bogra	1.04	5.74338E-05	0.01	509.49
Dinajpur	70.19	0.003876228	0.39	34385.97
Gaibandha	0.00	0	0.00	0.00
Joypurhat	0.00	0	0.00	0.00
Kurigram	0.00	0	0.00	0.00
Lalmonirhat	1.10	6.07473E-05	0.01	538.89
Naogaon	22.25	0.001228752	0.12	10900.24
Natore	0.00	0	0.00	0.00
Nawabganj	0.00	0	0.00	0.00

Nilphamari	11.88	0.000656071	0.07	5819.99
Pabna	0.00	0	0.00	0.00
Panchagarh	15.35	0.000847701	0.08	7519.94
Rajshahi	1.51	8.33894E-05	0.01	739.75
Rangpur	11.47	0.000633428	0.06	5619.13
Sirajganj	0.06	3.31349E-06	0.00	29.39
Thakurgaon	6.08	0.000335767	0.03	2978.58
Habiganj	108.99	0.00601895	0.60	53394.03
Maulvibazar	310.00	0.017119685	1.71	151868.50
Sunamganj	22.86	0.001262439	0.13	11199.08
Sylhet	56.29	0.003108603	0.31	27576.38
Total	18107.81	1	100	8870987

[a]district wise data of forests area in 1998 was collected from BBS (2002) .

Table C2 Estimated amount of biomass from forests and forestry-industry residues by districts in 2003

C3 Urban and Rural Population

Total population in Bangladesh in 2003: 138.1 million (World Bank, 2005)

Name of district	Population in 1998[a] (in 10^4)			Fraction of total population in 1998		Population in 2003 (in 10^4)		
	Rural	Urban	Total	Rural	Urban	Rural	Urban	Total
Barguna	79	9	88	0.006445349	0.000734280	89.01	10.14	99.15
Barisal	208.4	41.1	249.5	0.017002668	0.003353213	234.81	46.31	281.11
Bhola	145.5	23.8	169.3	0.011870865	0.001941763	163.94	26.82	190.75
Jhalokati	64.6	10.9	75.5	0.005270501	0.000889295	72.79	12.28	85.07
Patuakhali	125.8	17	142.8	0.010263607	0.001386974	141.74	19.15	160.89
Pirojpur	103.2	16	119.2	0.008419747	0.001305387	116.28	18.03	134.30
Bandarban	19.1	8	27.1	0.001558306	0.000652694	21.52	9.01	30.53
Brahmanbaria	214.9	34.2	249.1	0.017532981	0.002790265	242.13	38.53	280.66
Chandpur	219.7	15.8	235.5	0.017924598	0.001289070	247.54	17.80	265.34
Chittagong	322.9	296.4	619.3	0.026344345	0.024182297	363.82	333.96	697.77
Comilla	418.3	50.8	469.1	0.034127716	0.004144604	471.30	57.24	528.54
Cox's Bazar	141.4	25.3	166.7	0.011536359	0.002064143	159.32	28.51	187.82
Feni	114.3	13.5	127.8	0.009325360	0.001101420	128.78	15.21	143.99
Khagrachari	27.4	12.6	40	0.002235476	0.001027992	30.87	14.20	45.07
Lakshmipur	127.7	24	151.7	0.010418621	0.001958081	143.88	27.04	170.92
Noakhali	227.2	30.2	257.4	0.018536498	0.002463918	255.99	34.03	290.02
Rangamati	30	15.7	45.7	0.002447601	0.001280911	33.80	17.69	51.49
Dhaka	70.1	673.3	743.4	0.005719228	0.054932324	78.98	758.62	837.60
Faridpur	150.6	19.8	170.4	0.012286957	0.001615417	169.68	22.31	191.99
Gazipur	113.5	73.9	187.4	0.009260090	0.006029257	127.88	83.26	211.15
Gopalganj	108.8	10.2	119	0.008876633	0.000832184	122.59	11.49	134.08
Jamalpur	186.8	27.3	214.1	0.015240395	0.002227317	210.47	30.76	241.23

Kishoreganj	225.3	35.4	260.7	0.018381483	0.002888169	253.85	39.89	293.73
Madaripur	109.2	11.4	120.6	0.008909267	0.000930088	123.04	12.84	135.88
Manikganj	119.2	12.4	131.6	0.009725134	0.001011675	134.30	13.97	148.28
Munshiganj	118.9	14.2	133.1	0.009700658	0.001158531	133.97	16.00	149.97
Mymensingh	395.8	53.4	449.2	0.032292015	0.004356730	445.95	60.17	506.12
Narayanganj	95.8	91.1	186.9	0.007816006	0.007432548	107.94	102.64	210.58
Narsingdi	156	32	188	0.012727525	0.002610774	175.77	36.05	211.82
Netrokona	178.9	18.2	197.1	0.014595860	0.001484878	201.57	20.51	222.07
Rajbari	84.2	11.2	95.4	0.006869600	0.000913771	94.87	12.62	107.49
Shariatpur	97.7	9.5	107.2	0.007971020	0.000775074	110.08	10.70	120.78
Sherpur	115.9	14.2	130.1	0.009455898	0.001158531	130.59	16.00	146.59
Tangail	305.4	37.1	342.5	0.024916578	0.003026866	344.10	41.80	385.90
Bagerhat	139.1	24	163.1	0.011348710	0.001958081	156.73	27.04	183.77
Chuadanga	67	25.1	92.1	0.005466309	0.002047826	75.49	28.28	103.77
Jessore	205.7	36	241.7	0.016782384	0.002937121	231.76	40.56	272.33
Jhenaidah	133.4	22.6	156	0.010883666	0.001843859	150.30	25.46	175.77
Khulna	109.5	126.4	235.9	0.008933743	0.010312559	123.37	142.42	265.79
Kushtia	150.1	21.5	171.6	0.012246163	0.001754114	169.12	24.22	193.34
Magura	75.3	7.5	82.8	0.006143478	0.000611900	84.84	8.45	93.29
Meherpur	50.2	6.2	56.4	0.004095652	0.000505838	56.56	6.99	63.55
Narail	63	8.6	71.6	0.005139962	0.000701646	70.98	9.69	80.67
Satkhira	162.9	18	180.9	0.013290473	0.001468561	183.54	20.28	203.82
Bogra	270.9	38.8	309.7	0.022101837	0.003165564	305.23	43.72	348.94
Dinajpur	224.6	36.9	261.5	0.018324372	0.003010549	253.06	41.58	294.64
Gaibandha	206.2	19.6	225.8	0.016823177	0.001599099	232.33	22.08	254.41
Joypurhat	78	10.4	88.4	0.006363762	0.000848502	87.88	11.72	99.60
Kurigram	157.4	26.6	184	0.012841746	0.002170206	177.34	29.97	207.32
Lalmonirhat	91.3	12.9	104.2	0.007448866	0.001052468	102.87	14.53	117.40
Naogaon	224.9	23.7	248.6	0.018348848	0.001933605	253.40	26.70	280.10
Natore	132.5	19.7	152.2	0.010810237	0.001607258	149.29	22.20	171.49
Nawabganj	111.2	24.5	135.7	0.009072441	0.001998874	125.29	27.60	152.89

Nilphamari	134.1	20.3	154.4	0.010940776	0.001656210	151.09	22.87	173.96
Pabna	182.5	37.1	219.6	0.014889572	0.003026866	205.62	41.80	247.43
Panchaghar	70.3	7.6	77.9	0.005735545	0.000620059	79.21	8.56	87.77
Rajshahi	147.6	76.5	224.1	0.012042197	0.006241382	166.30	86.19	252.50
Rangpur	205.1	44.7	249.8	0.016733432	0.003646925	231.09	50.36	281.45
Serajganj	227.6	33.1	260.7	0.018569132	0.002700520	256.44	37.29	293.73
Thakurgaon	103.5	12.4	115.9	0.008444223	0.001011675	116.61	13.97	130.59
Habiganj	159.2	16.7	175.9	0.012988602	0.001362498	179.37	18.82	198.19
Maulavibazar	142.9	15.2	158.1	0.011658739	0.001240118	161.01	17.13	178.13
Sunamganj	180.3	17.5	197.8	0.014710082	0.001427767	203.15	19.72	222.86
Sylhet	207.6	42.5	250.1	0.016937399	0.003467435	233.91	47.89	281.79
Total Bangladesh	9635.4	2621.5	12256.9			10856.33	2953.67	13809.97

[a]district wise data of rural and urban population in 1998 was collected from BBS (2002).

Table C3 Estimated rural and urban population by districts in 2003

C4 Farm animals and Poultry Population

Type	Number (Heads)	
	In 1996	In 2003
Cattle and Buffaloes	22194906	25350000
Sheep and Goat	14609788	35760000
Poultry	126667861	153000000

Table C4 Total number of farm animal and poultry in Bangladesh
(BBS, 2000; and FAOSTAT, 2004)

Name of district	Number of cattle and buffalos[a] (Heads)			Number of sheep and goats[a] (Heads)			Number of poultry birds[a] (Heads)		
	Total in 1996	Fraction of total in 1996	Estimated in 2003	Total in 1996	Fraction of total in 1996	Estimated in 2003	Total in 1996	Fraction of total in 1996	Estimated in 2003
Barguna	285605	0.012868	326205	91225	0.006244	223289	1785445	0.014095	2156609
Barisal	413985	0.018652	472835	163293	0.011177	399688	3176714	0.025079	3837100
Bhola	265335	0.011955	303053	166920	0.011425	408566	3071880	0.024251	3710473
Jhalokati	152031	0.006850	173643	46022	0.003150	112647	1074882	0.008486	1298332
Patuakhali	432992	0.019509	494544	158121	0.010823	387029	3132245	0.024728	3783387
Pirojpur	256122	0.011540	292531	77832	0.005327	190507	1852116	0.014622	2237140
Bandarban	92085	0.004149	105175	50550	0.003460	123730	461140	0.003641	557003
Brahmanbaria	384812	0.017338	439515	162675	0.011135	398175	2806252	0.022154	3389625
Chandpur	283159	0.012758	323411	150725	0.010317	368926	2752851	0.021733	3325123
Chittagong	651868	0.029370	744534	249719	0.017093	611231	3774710	0.029800	4559409
Comilla	729296	0.032859	832968	435994	0.029843	1067171	5757881	0.045457	6954849
Cox's Bazar	261660	0.011789	298856	116655	0.007985	285533	2109280	0.016652	2547764
Feni	179991	0.008110	205577	68204	0.004668	166941	1835471	0.014490	2217035
Khagrachari	119348	0.005377	136314	81259	0.005562	198896	640703	0.005058	773894
Lakshmipur	192359	0.008667	219704	102688	0.007029	251347	2213051	0.017471	2673107
Noakhali	327699	0.014765	374283	185931	0.012726	455098	3873540	0.030580	4678784
Rangamati	110000	0.004956	125637	86655	0.005931	212103	692225	0.005465	836127
Dhaka	142202	0.006407	162417	61316	0.004197	150082	684651	0.005405	826979
Faridpur	320356	0.014434	365896	225494	0.015434	551936	1521008	0.012008	1837200
Gazipur	309289	0.013935	353256	228155	0.015617	558449	1302696	0.010284	1573505
Gopalganj	210813	0.009498	240781	75981	0.005201	185977	936772	0.007395	1131511
Jamalpur	421270	0.018980	481155	244520	0.016737	598505	2010675	0.015874	2428661
Kishoreganj	455353	0.020516	520083	222602	0.015236	544857	2536205	0.020022	3063440
Madaripur	199683	0.008997	228069	137751	0.009429	337170	1304381	0.010298	1575540
Manikganj	256176	0.011542	292592	166220	0.011377	406852	1015842	0.008020	1227019
Munshiganj	166108	0.007484	189721	62625	0.004287	153286	1008250	0.007960	1217848
Mymensingh	940598	0.042379	1074308	669411	0.045819	1638500	4655152	0.036751	5622881
Narayanganj	94804	0.004271	108281	109529	0.007497	268091	856192	0.006759	1034180
Narsingdi	288419	0.012995	329419	250141	0.017121	612264	1962460	0.015493	2370423
Netrokona	446793	0.020130	510306	210130	0.014383	514330	2201217	0.017378	2658813
Rajbari	190170	0.008568	217203	142453	0.009751	348679	773848	0.006109	934718
Shariatpur	175300	0.007898	200220	114150	0.007813	279402	1474661	0.011642	1781218
Sherpur	264460	0.011915	302054	165425	0.011323	404906	1216955	0.009607	1469940
Tangail	708293	0.031912	808980	467626	0.032008	1144596	3459218	0.027309	4178332

Bagerhat	283460	0.012771	323755	134195	0.009185	328466	1734136	0.013690	2094634
Chuadanga	178854	0.008058	204279	230502	0.015777	564194	1156336	0.009129	1396719
Jessore	609042	0.027441	695620	542020	0.037100	1326688	3380796	0.026690	4083607
Jhenaidah	398833	0.017970	455529	301130	0.020612	737068	1959941	0.015473	2367380
Khulna	314080	0.014151	358728	165338	0.011317	404694	1362006	0.010753	1645144
Kushtia	317750	0.014316	362919	275730	0.018873	674897	1443765	0.011398	1743900
Magura	212435	0.009571	242633	132502	0.009069	324322	787561	0.006218	951282
Meherpur	105502	0.004753	120500	164793	0.011280	403360	732006	0.005779	884178
Narail	164728	0.007422	188145	78047	0.005342	191034	635279	0.005015	767343
Satkhira	428329	0.019299	489218	352689	0.024141	863268	2119215	0.016730	2559765
Bogra	585529	0.026381	668764	465537	0.031865	1139483	4076676	0.032184	4924149
Dinajpur	826610	0.037243	944116	641410	0.043903	1569963	3857994	0.030458	4660007
Gaibandha	487977	0.021986	557345	398262	0.027260	974816	2637769	0.020824	3186117
Joypurhat	239965	0.010812	274077	204540	0.014000	500647	1581649	0.012487	1910447
Kurigram	427021	0.019240	487724	310166	0.021230	759185	2117310	0.016715	2557463
Lalmonirhat	280085	0.012619	319900	244000	0.016701	597232	966620	0.007631	1167564
Naogaon	687806	0.030989	785580	578118	0.039571	1415044	3499403	0.027627	4226871
Natore	279834	0.012608	319614	263564	0.018040	645119	1652954	0.013050	1996576
Nawabganj	249654	0.011248	285143	263222	0.018017	644282	1025611	0.008097	1238818
Nilphamari	360690	0.016251	411964	326240	0.022330	798529	1565370	0.012358	1890784
Pabna	389256	0.017538	444590	354714	0.024279	868224	1904688	0.015037	2300641
Panchaghar	257169	0.011587	293727	210519	0.014409	515282	832383	0.006571	1005422
Rajshahi	329092	0.014827	375874	341112	0.023348	834931	1884599	0.014878	2276376
Rangpur	574005	0.025862	655602	466947	0.031961	1142934	2923820	0.023083	3531633
Serajganj	461930	0.020812	527595	274212	0.018769	671182	2432841	0.019206	2938588
Thakurgaon	415146	0.018705	474161	373629	0.025574	914522	1206224	0.009523	1456978
Habiganj	374091	0.016855	427270	138314	0.009467	338548	1672587	0.013205	2020290
Maulavibazar	326237	0.014699	372613	167663	0.011476	410384	1371912	0.010831	1657110
Sunamganj	439470	0.019800	501942	133196	0.009117	326020	1893331	0.014947	2286923
Sylhet	461892	0.020811	527552	129480	0.008863	316925	2322510	0.018335	2805321

[a] district wise distribution of farm animals and poultry heads in 1996 were collected from BBS (2000).

Table C5 District wise estimated number of farm animals and poultry population (Heads) in 2003

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APPENDIX D
FEASIBLE TECHNOLOGIES: COST AND EFFICIENCIENCY

D1 Gasification

Country	Type of gasifier	Biomass input	Cold gas efficiency of gasifier (%)	Type of prime mover	Electricity-generating capacity (kW)	Electrical efficiency (%)	Capital investment cost (September 2004 value) (US$/kW)	Reference
China	Downdraft	Wood chip, tree bark	70	-	2-3	-	-	Wu et al. (2002)
China	-	Wood waste	-	-	2.5 -30	11-14	-	Lin et al. (1998)
India	-	Rice husk	55	Compression ignition engine	3-150	16	-	Kapur et al. (1996)
India	-	Wood	-	Compression ignition engine	3.5	18	1109	Ravindranath and Hall (1995)
India	-	Wood	-	Compression ignition engine	4.4	18	1963	Ravindranath and Hall (1995)
Indonesia	-	Wood	-	Compression ignition engine	10	15	2058	Stassen (1995)
Indonesia	-	Wood	-	Spark ignition engine	10	12	2327	Stassen (1995)
India	-	Sugarcane leaves	59.6	Compression ignition engine	11	15.7	-	Jorapur and Rajvanshi (1995)
Indonesia	Downdraft	Rubber wood	-	Compression ignition engine	15	21.8	-	Stassen (1995)
Indonesia	Cross-draft	Rice husk	-	Compression ignition engine	15	14	-	Stassen (1995)
Vanuatu	Downdraft	Wood	-	Spark ignition engine	23.7	16.2	-	Stassen (1995)
Indonesia	Downdraft	Wood waste	-	Spark ignition engine	26.2	18.9	-	Stassen (1995)
-	-	Wood waste	-	Spark ignition engine	30	16	1512	Stassen (1995)
-	-	Rice husk	-	Spark ignition engine	30	9	1512	Stassen (1995)

-	-	Wood waste	-	Compression ignition engine	30	18	1311	Stassen (1995)
-	-	Rice husk	-	Compression ignition engine	30	10	1311	Stassen (1995)
Seychelles	Downdraft	Coconut shell and husks	-	Spark ignition engine	35	16	-	Stassen (1995)
-	-	Wood	-	Spark ignition engine	40	16	1329	Siemons (2001)
Brazil		-	-	Micro gas-turbine	45	-	1377	Lora and Nogueira (1998)
India	-	-	-	Compression ignition engine	50	-	711	Desipower (2004)
India	-	-	-	Spark ignition engine	55	-	535	Desipower (2004)
China		-	-	Spark ignition engine	60 - 2000	15-18	-	Lin et al. (1998)
Brazil	-	-	-	Spark ignition engine	75	-	850	Lora and Nogueira (1998)
-	-	-	-	Compression ignition engine	96	-	1703	Ravindranath and Hall (1995)
-	-	Wood	-	Spark ignition engine	100	17	941	Stassen (1995)
-	-	Rice husk	-	Spark ignition engine	100	10	941	Stassen (1995)
-	-	Wood	-	Compression ignition engine	100	19	848	Stassen (1995)
-	-	Rice husk	-	Compression ignition engine	100	11	848	Stassen (1995)
-	-	-	-	Compression ignition engine	100	-	872	Kartha and Larson (2000)
-	-	Wood	-	Spark ignition engine	160	22	2046	Siemons (2001)
China	-	-	-	Spark ignition engine	160	-	906	RWEDP (2002)
China	Downdraft	-	-	Spark ignition engine	200	12.5	348	Wu et al. (2002)
China	CFB	Straw, husk, sawdust	65 - 75	-	400-2000	-	-	Leung et al. (2004)

Finland	-	Wood residues	-	Spark ignition engine	470	24	-	Kirjavainen et al. (2004)
China	CFB	Corn straw	-	Spark ignition engine	600	-	431	Leung et al. (2004)
-	Downdraft fixed-bed gasifier	Wood waste	70	Spark ignition engine	1000	17	3699	Quaak et al. (1999)
China	CFB	-	-	Spark ignition engine	1000	17	387	Wu et al. (2002)
China	CFB	-	-	Spark ignition engine	1000	-	400	Leung et al. (2004)
China	CFB	Rice hull, wood waste	67-75	Spark ignition engine	1000-1200	-	-	Wu et al. (2002)
Denmark	Down-draft	Wood	-	-	1300	22	-	Kirjavaine et al. (2004)
Denmark	Updraft	Wood chips	-	Spark ignition engine	1300–1500	32 – 35	-	Kirjavainen et al. (2004)
China	CFB	-	-	Spark ignition engine	1500	-	328	Leung et al. (2004)
China	CFB	Agricultural residues	-	Spark ignition engine	1500	17	-	Lin et al. (1998)
China	CFB	-	-	Spark ignition engine	2000	-	320	Leung et al. (2004)
-	CFB	-	70	Combined cycle gas turbine	5000	35	3482	Quaak et al. (1999)
China	-	-	-	Combined cycle gas turbine	5000-50000	33 – 45	-	Lin et al. (1998)
-	-	-	-	Combined cycle gas turbine	21000	24	-	Quaak et al. (1999)
India	-	Wood, agricultural waste	60-70	-	-	-	-	Teriin (2004)

-	Downdraft	Wood	65 -75	-	-	-	-	Quaak et al. (1999)
-	Updraft	Wood	40-60	-	-	-	-	Quaak et al. (1999)
-	Open-core	Wood	35-50	-	-	-		Quaak et al. (1999)
-	-	Wood from plantation	-	Combined cycle gas turbine	30000	35	1744	Karha and Larson (2000)
-	-	-	-	Gas turbine	50000	-	1533	Ahmed (1994)

Note: Compression ignition engines are operated in dual fuel mood (producer gas and diesel)

Table D1 Efficiency and capital investment cost of biomass gasifier – based electricity generation plant

Elements of investment cost	Electricity-generating capacity (kW)									
	3	5	10	20	40	100	150	200	300	500
Cost of gasifier (1000 Rs.)[a]	32	51	87	146	226	446	550	800	1250	1800
Cost of diesel engine generator set (1000Rs.)[a]	34	45	81	164	279	629	950	1300	2150	3600
Total cost (1000Rs.)[a]	66	96	168	310	505	1075	1500	2100	3400	5400
Total cost (US$ in 1996)[a]	1849	2690	4707	8686	14150	30121	42030	58842	95268	151308
Specific cost (US$/kW, September 2004 value)[b]	744	650	569	524	428	364	338	355	383	366
Cost of freight and installation[c] (US$/kW)	-	-	-	-	-	-	100	100	100	100
Total cost of training and commissioning[c] (US$)	2890	2890	2890	2890	2890	2890	2890	2890	2890	2890
Total specific capital investment cost[c] (US$/kW)	-	-	-	-	-	-	457	469	493	472

[a] US $ 1 = 35.50 Indian Rupees (Rs.), in November 1996

[b] Converted taking account the inflation rate

[c] see section 5.2.5

Table D2 Investment cost of biomass gasifier-based electricity-generation systems in India (Tripathi et al. 1997)

D2 Anaerobic Digestion

Plant	Country	Fuel and type of digester	Biomass input to the digester	Prime mover	Electricity-generating capacity (kW)	Electrical efficiency at full load (%)	Capital investment cost (September 2004 value) (US$/kW)	Reference
Pura community biogas plant	India	Biogas and diesel, Floating cover digester	Animal waste	Compression ignition engine	5	-	1793	Ravindranath and Hall (1995)
-	-	Biogas	-	Spark ignition engine	10-200	25-45 (23-40)[a]	-	Alanne and Saari (2004)
-	USA	Biogas Mesophilic, flexible top digester with plug flow	Animal waste	Spark ignition engine	40	-	5267[b]	EPA (2003)
-	USA	Biogas Mesophilic,	Animal waste	Spark ignition engine	55	-	8618	EPA (2003)
-	USA	Biogas Mesophilic, flexible top digester with plug flow	Animal waste	Spark ignition engine	100	-	4066[b]	EPA (2003)
-	-	Biogas	-	Spark ignition engine	100	28[e]	4323[e]	Kranzl et al. (2004)
-	-	Biogas	Sewage sludge	Spark ignition engine	100	32[e]	3448[e]	Kranzl et al. (2004)

AA dairy farm	USA	Biogas	Animal waste	Spark ignition engine	130	30 (20)[a]	2423	Martin (2003)
-	USA	Biogas Mesophilic, fixed top digester with plug flow	Poulytry (Chicken) waste	Spark ignition engine	150	-	877[b]	EPA (2003)
-	USA	Biogas Mesophilic, fixed top digester	Poultry (ducks) waste	Spark ignition engine	180	-	2925[c]	EPA (2003)
-	-	Biogas	Sewage sludge	Spark ignition engine	200	30[e]	3087[e]	Kranzl et al. (2004)
		Biogas Mesophilic, flexible top digester with plug flow	Animal waste	Spark ignition engine	246		3746	EPA (2003)
-	-	-	Biogas	Spark ignition engine	250	32[e]	3294[e]	Kranzl et al. (2004)
-	China	Biogas	Pig manure	Spark ignition engine	314.57 (~315)	25	1094	World Bank (1996)
-	USA	Biogas Mesophilic, flexible top digester with plug flow	Animal waste	Spark ignition engine	360		3511	EPA (2003)
Laholm	Sweden	Biogas	-	Spark ignition engine	450	38	-	Kirjavainen et al. (2004)
-	USA	Biogas Mesophilic, fixed top digester with plug flow	Animal waste	Spark ignition engine	500		3792[b]	EPA (2003)

-	USA	-	Animal waste	Spark ignition engine	500	29[d]	-	EERE (2002)
-	-	Biogas	-	Spark ignition engine	500	34[e]	2573[e]	Kranzl et al. (2004)
-	-	-	Sewage sludge	Spark ignition engine	600	32[e]	2315[e]	Kranzl et al. (2004)
Jönköping	Sweden	Biogas	-	Spark ignition engine	990	38	-	Kirjavainen et al. (2004)
-	-	Biogas	-	Spark ignition engine	-	25	-	Picken (1989)
-	-	Biogas	-	Compression ignition engine	-	30-35	-	Picken (1989)
-	-	Biogas	Animal waste	-	-	20-22	-	Schmidt and Pinapati (2000)
-	-	Biogas	-	Stirling engine	-	30	-	Lin et al. (1998)

Note: Compression ignition engines are operated in dual fuel mood (producer gas and diesel)
a Figures in bracket represents the efficiency at part load
b Biogas is used for the production of electricity generation and hot water
c Biogas is used for electricity generation and digester heating
d Efficiency has been calculated for calorific value of biogas = 23 MJ/kg
e Data used for simulation in the Altener program of the European Commission

Table D3 Efficiency and capital investment cost of biomass anaerobic digestion-based electricity generation plants

Digester type	Country	Digester capacity (m^3)	Capital investment cost (September 2004 value) (US$/$m^3$)	Reference
Floating drum	India	2	163	Singh and Sooch (2004)
Fixed dome (Deenbandhu Model)	India	2	84	Singh and Sooch (2004)
Fixed dome (Janata Model)	India	2	140	Singh and Sooch (2004)
-	Pakistan	3	69	RWEDP (2002)
-	Nepal	4	72	RWEDP (2002)
Floating drum	India	6	85	Singh and Sooch (2004)
Fixed dome (Janata Model)	India	6	80	Singh and Sooch (2004)
Fixed dome (Deenbandhu Model)	India	6	47	Singh and Sooch (2004)
Fixed dome	Sudan	7	165	Omer and Fadalla (2003)
Fixed dome	Nepal	8	48	Devkota (2003)
Fixed dome	Nepal	10	44	Devkota (2003)
-	Nepal	20	40	RWEDP (2002)

Table D4 Capital investment cost of biogas digester in developing countries

D3 Direct Combustion

Plant	Country	Prime mover	Biomass input for combustion	Electricity-generating capacity (kW)	Electrical efficiency (%)	Capital investment cost (September 2004 value) (US$/kW)	Reference
-	-	Stirling engine	-	2- 50	15 – 35	-	Alanne and Saari (2004)
-	Austria	Stirling engine	Wood chip	3	28	-	Podesser (1999)
Skarp Salling	Denmark	Stirling engine	Wood chips	28	18	-	Kirjavainen et al. (2004)
-	Denmark	Stirling engine	-	30	22	-	Carlsen (1996)
-	Denmark	Stirling engine	-	150	26	-	Carlsen (1996)
Hjordkaer	Denmark	Steam engine	Wood chips, biowaste	600	16	-	Kirjavainen et al. (2004)
Kiuruvesi	Finland	Grate firing and Steam engine	Tree bark, sawdust and wood chips	900	11	-	Kirjavainen et al. (2004)
-	-	Steam turbine	-	1000	14	4974	Quaak et al. (1999)
-	-	-	Agricultural waste	1000	26[a]	2676[a]	Kranzl et al. (2004)
-	-	Mass-burn boiler and steam turbine	Biowastes	1000	18[a]	5918[a]	Kranzl et al. (2004)
-	-	Steam turbine	Forestry and agricultural products/residues	1000	26[a]	2573[a]	Kranzl et al. (2004)
Slagelse	Denmark	Grate firing boiler and steam turbine	Straw	1170	29	-	Kirjavainen et al. (2004)

Forssjö	Sweden	Stoker boiler and steam turbine	Wood residues	1500	20	-	Kirjavainen et al. (2004)
Tranås Energi AB	Sweden	Grate firing and steam turbine	Sawdust, tree bark	1600	14. 5	-	Kirjavainen et al. (2004)
Myresjöhus	Sweden	Grate firing and steam turbine	Sawdust and tree bark	2000	20	-	Kirjavainen et al. (2004)
Hallsberg	Sweden	Multi-bed BFB	Wood	2005	14	-	Kirjavainen et al. (2004)
Rudkøbing	Denmark	Grate firing and steam turbine	Straw	2300	22	-	Kirjavainen et al. (2004)
-	-	Steam turbine	Wood from plantation	3000	-	3859[b]	Ahmed (1994)
Malå	Sweden	Wood residues	BFB	3000	25	-	Kirjavainen et al. (2004)
-	Thailand	-	Wood	3200	-	3204	RWEDP (2002)
Kuhmo	Finland	CFB	Wood residues	4800	24	-	Kirjavainen et al. (2004)
-	-	Steam turbine	-	5000	28	3233	Quaak et al. (1999)
-	Indonesia	Steam turbine	Wood residues	5550	-	939	RWEDP (2002)
-	-	Steam turbine	Wood from plantation	10000	-	3110[b]	Ahmed (1994)
-	Malaysia	-	Wood residues	10000	-	818	RWEDP (2002)
-	India	CFB boiler and steam turbine	Straw	10000	-	-	Bhattacharya (1993)
-	-	-	Agricultural residues	25000	30[a]	2367[a]	Kranzl et al. (2004)
-	-	Steam turbine	Forestry and agricultural products/residues	25000	30[a]	2265[a]	Kranzl et al. (2004)

Delano I	USA	BFB bed boiler	Agricultural residues	27000	29	-	Broke et al. (1996)
-	Thailand	-		30000	-	2392	RWEDP (2002)
Händelöverk et CHP	Sweden	CFB boiler and steam turbine	Wood	46000	32	1486	Broke et al. (1996)
-	-	Steam turbine	-	50000	-	2320[b]	Ahmed (1994)
EPRI project	USA	Stoker boiler and steam turbine	Wood	50000	24.6	2339	Mcgowin and Wiltsee (1996)
EPRI project	USA	Fluid bed boiler and steam turbine	-	50000	24.6	2745	Mcgowin and Wiltsee (1996)
EPRI project	USA	Whole tree energy boiler and steam turbine	Whole tree	50000	32	2225	Mcgowin and Wiltsee (1996)
EPRI project	USA	Mass-burn boiler and steam turbine	MSW	50000	20.8	5529	Mcgowin and Wiltsee (1996)
EPRI, USA project	USA	Stoker boiler and steam turbine	RDF fired boiler	50000	20.7	5699	Mcgowin and Wiltsee (1996)
	USA	Travelling grate boiler and steam turbine	Wood	50000	30	2431	Broke et al. (1996)
	Thailand	-	Wood	100000	-	1879	RWEDP (2002)
-	-	Grate firing boiler	Forest waste, mill waste bagasee, tyres	-	23-26	-	Schmidt and Pinapati (2000)
-	-	Fluidized bed boiler and steam turbine	Forest/mill waste /stalks/straws/shells	-	27-28	-	Schmidt and Pinapati (2000)

a Data used for simulation for research in Altener program of the European Commission; b Including the cost of plantation

Table D5 Efficiency and capital investment cost of biomass direct combustion – based electricity generation plants

D4 Diesel Generators

Brand/ Manufacturer	Electricity-generating capacity (kW)	Electrical efficiency (%)	Reference
-	5	25	ITDG (2004)
-	10	30	Siemons (2001)
-	10	23	Stassen (1995)
-	14	30	Jorapur and Rajvanshi (1995)
-	30	25	Stassen (1995)
-	40	30	Siemons (2001)
-	50	35	ITDG (2004)
-	100	28	Stassen (1995)
-	160	35	Siemons (2001)
-	500	45	ITDG (2004)
Caterpillar Inc	1000	34	Willi (2001)
Caterpillar Inc	7500	44	Willi (2001)

Table D6 Electrical efficiencies of diesel generators

Brand/ Manufacturer	Electricity-generating capacity (kW)	Cost[a]		Reference
		(US$)	(US$/kW)	
Imperial Diesel Generator	20	6500	325	Independent Power Systems (2004)
Perkins	24	6840	285	GSO (2004)
Perkins	32	7825	245	GSO (2004)
Cummins Generator	32	8175	255	GSO (2004)
Cummins Generator	40	9125	228	GSO (2004)
Cummins Generator	50	9925	199	GSO (2004)
Perkins	52	8885	171	GSO (2004)
Cummins Generator	65	10925	168	GSO (2004)
Perkins	80	11375	142	GSO (2004)
Cummins Generator	85	13375	157	GSO (2004)
Perkins	90	12350	137	GSO (2004)
Perkins	120	15396	128	GSO (2004)
CCP Daewoo	125	18225	146	CCP (2004)
John Deere	125	19750	158	ADG (2004)
CCP Daewoo	150	19750	132	CCP (2004)
CCP Daewoo	200	22700	114	CCP (2004)
CCP Daewoo	250	26150	105	CCP (2004)
Cummins Generator	275	31750	115	GSO (2004)
CCP Daewoo	300	33250	111	CCP (2004)
CCP Daewoo	350	35500	101	CCP (2004)
CCP Daewoo	375	44600	119	CCP (2004)
CCP Daewoo	400	45100	113	CCP (2004)
CCP Daewoo	450	45900	102	CCP (2004)
CCP Daewoo	500	63700	127	CCP (2004)
CCP Daewoo	600	69500	116	CCP (2004)
Kato	1050	105000	100	Utility Warehouse (2004)

[a] All costs are in September 2004 value

Table D7 Cost of diesel generator systems

D5 References

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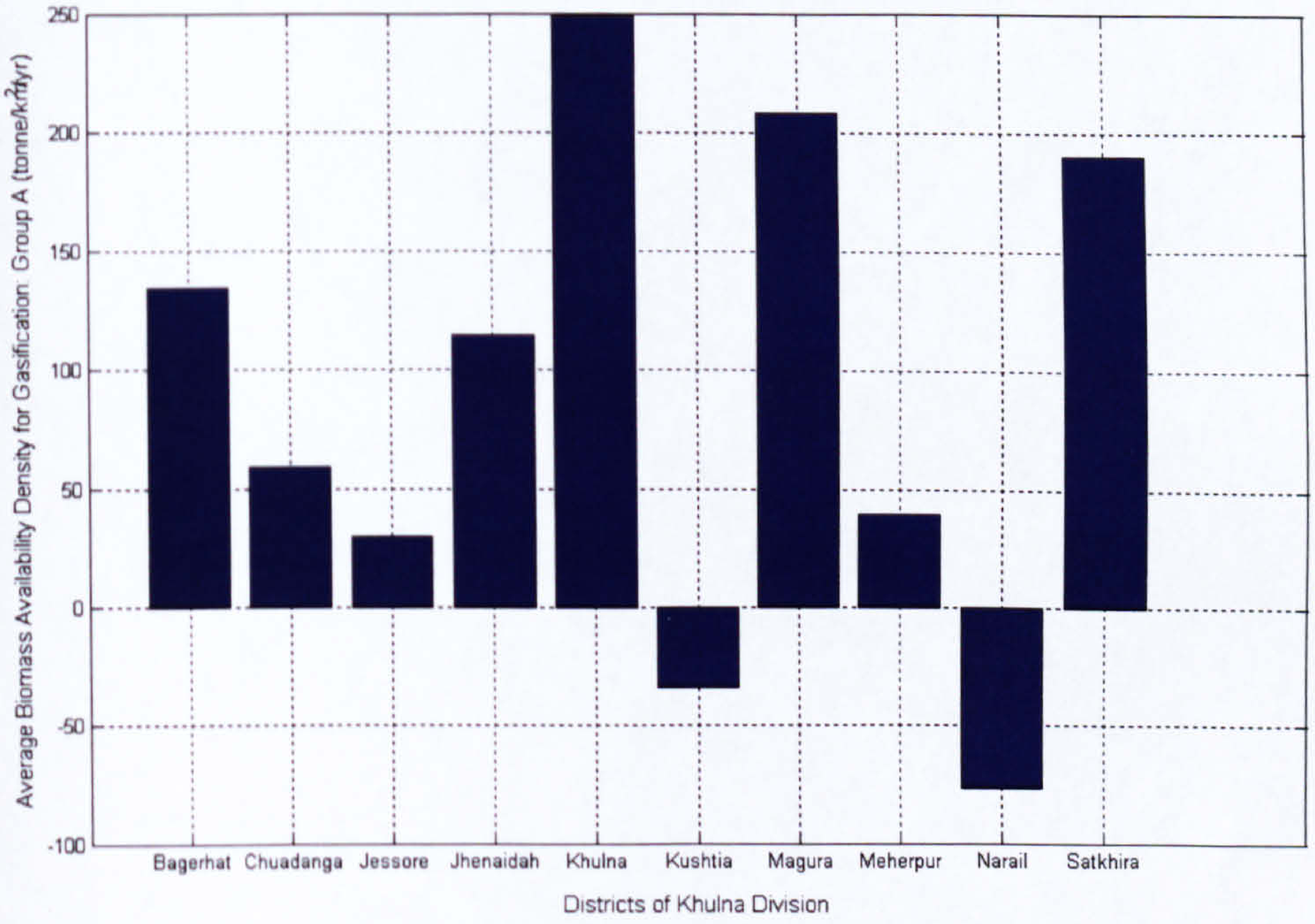
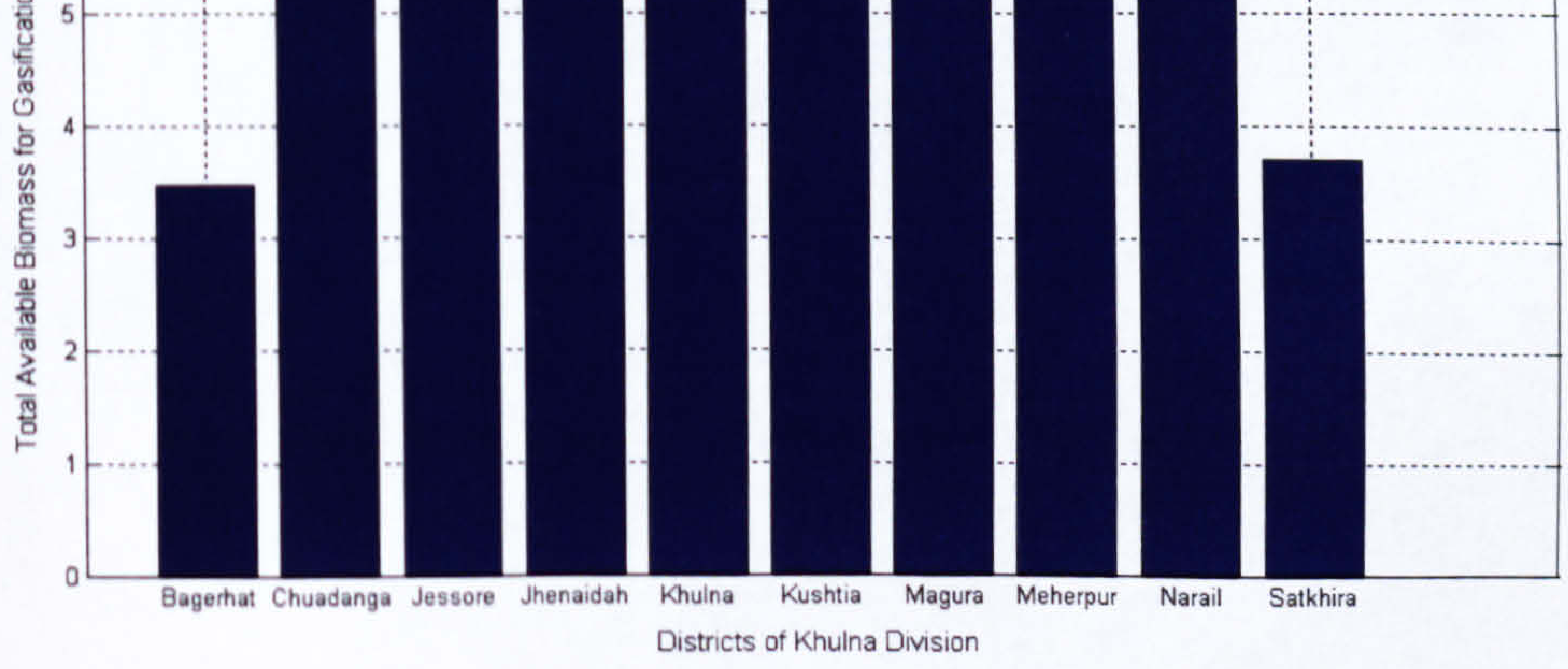
APPENDIX E
RESULTS BY DISTRICT: KHULNA DIVISION

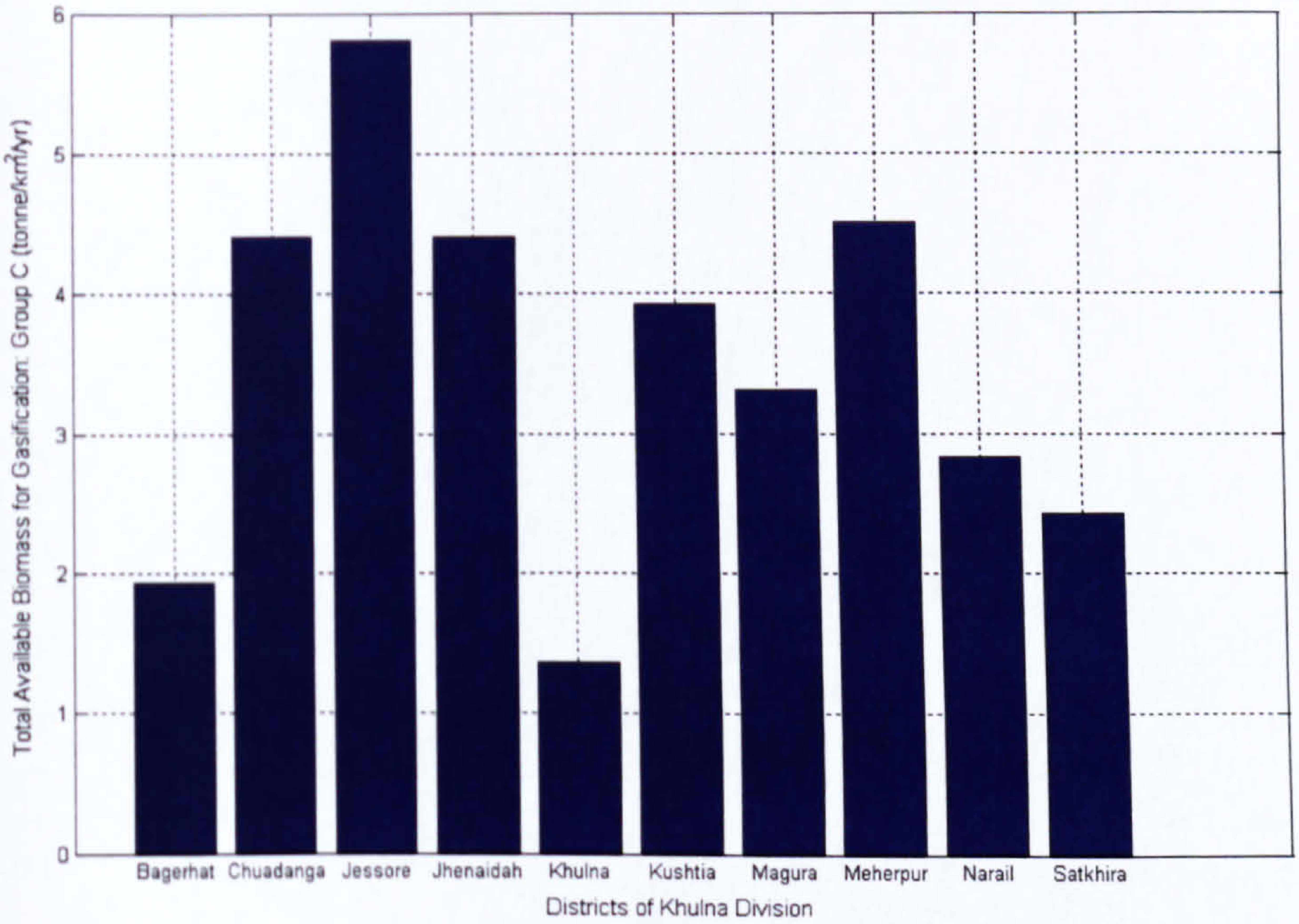
E1 Gasification Electricity

Group A: Agricultural wastes and forestry residues
Group B; Gasifiable/Combustible parts of MSW and Group C: Poultry wastes

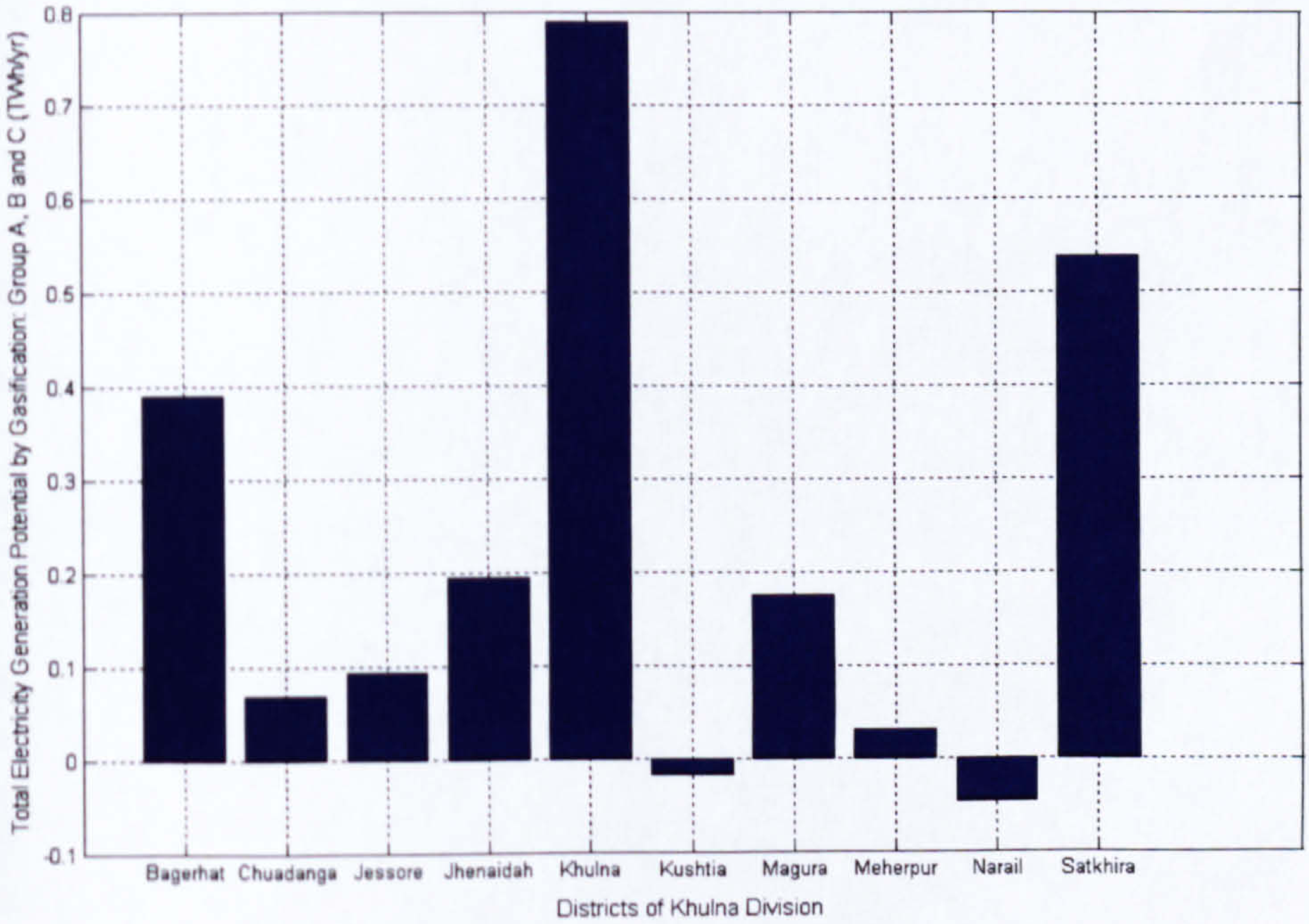
E1.1 Biomass Availability



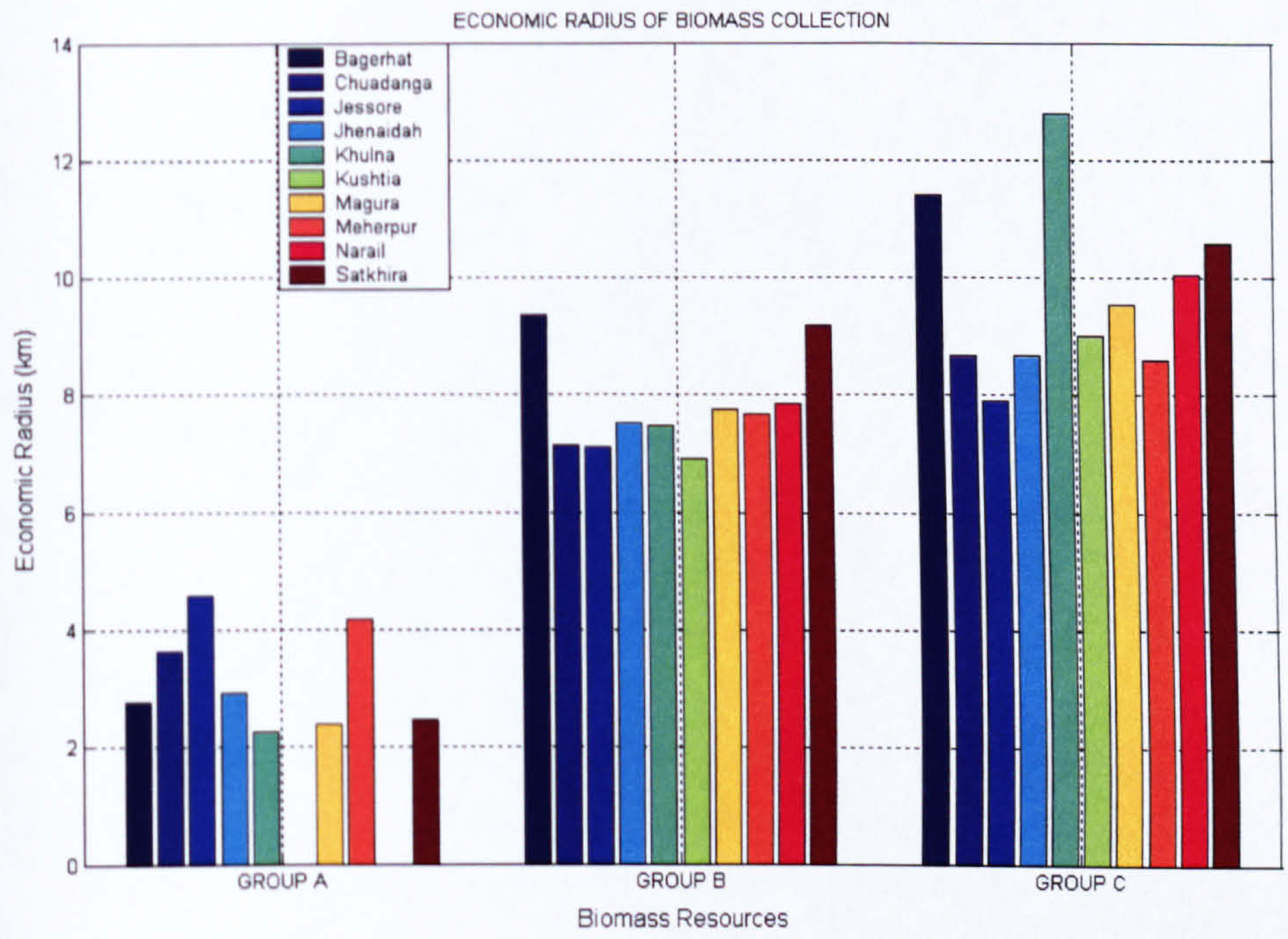


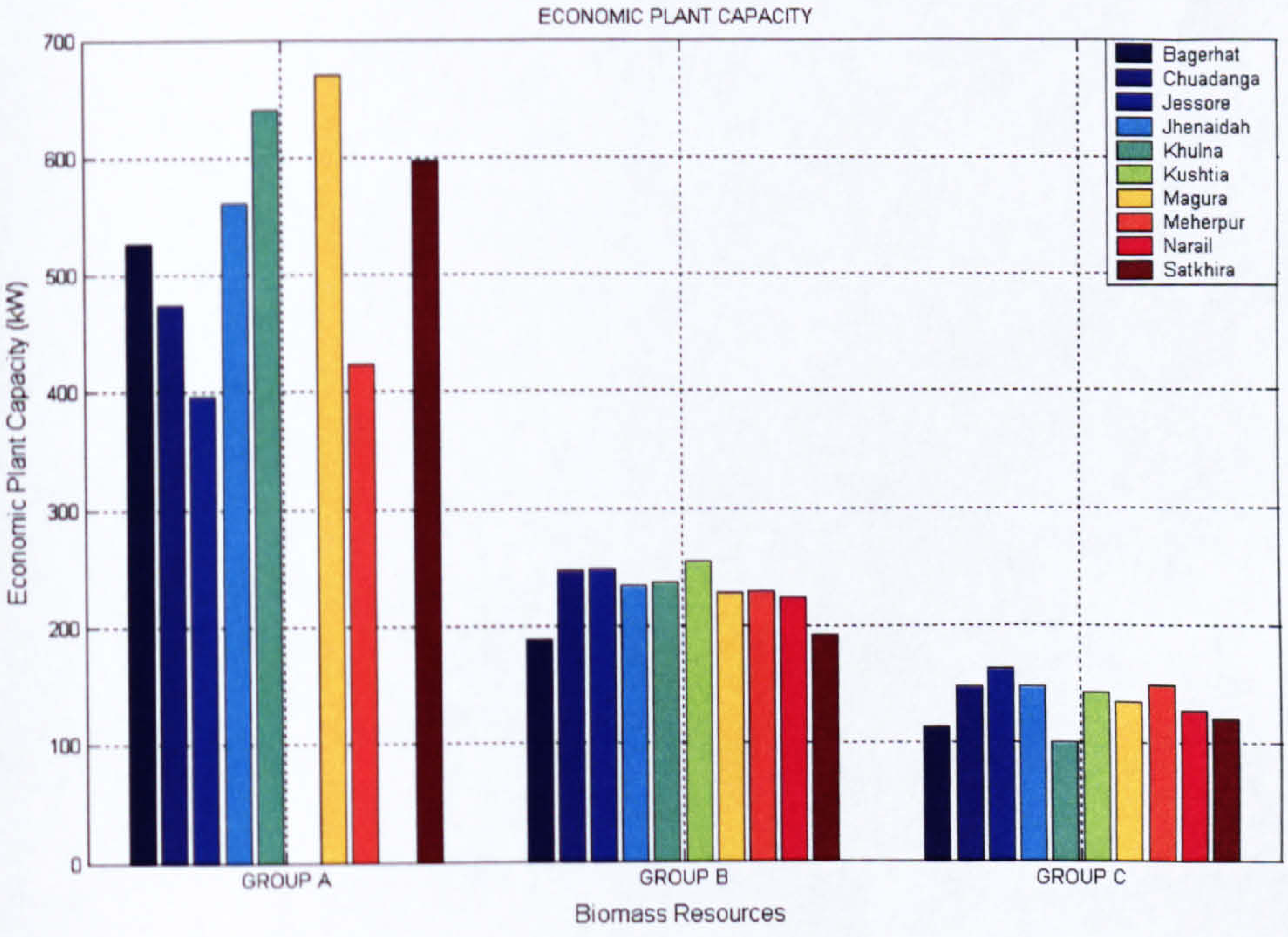


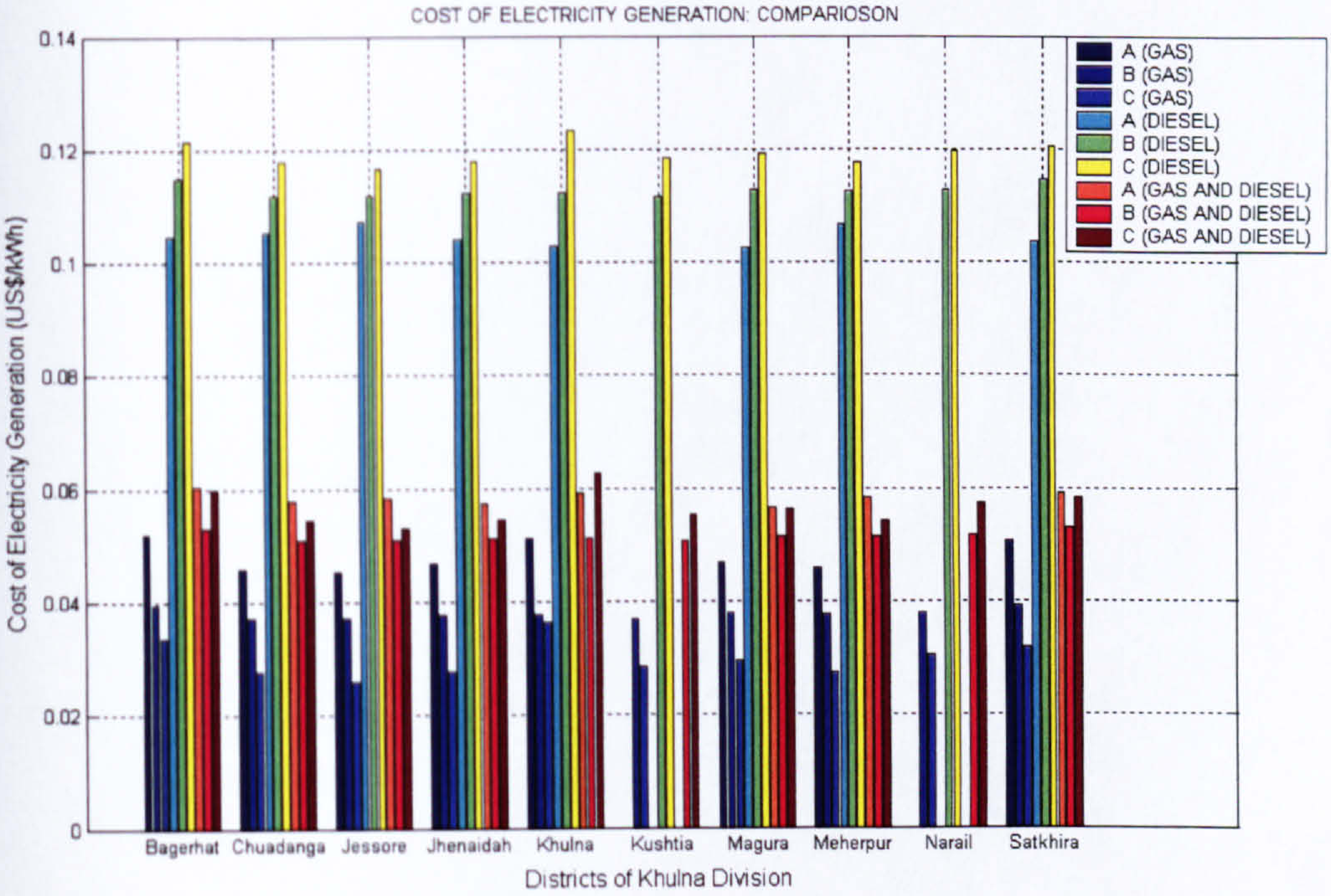
E1.2 Total Electricity Generation Potential

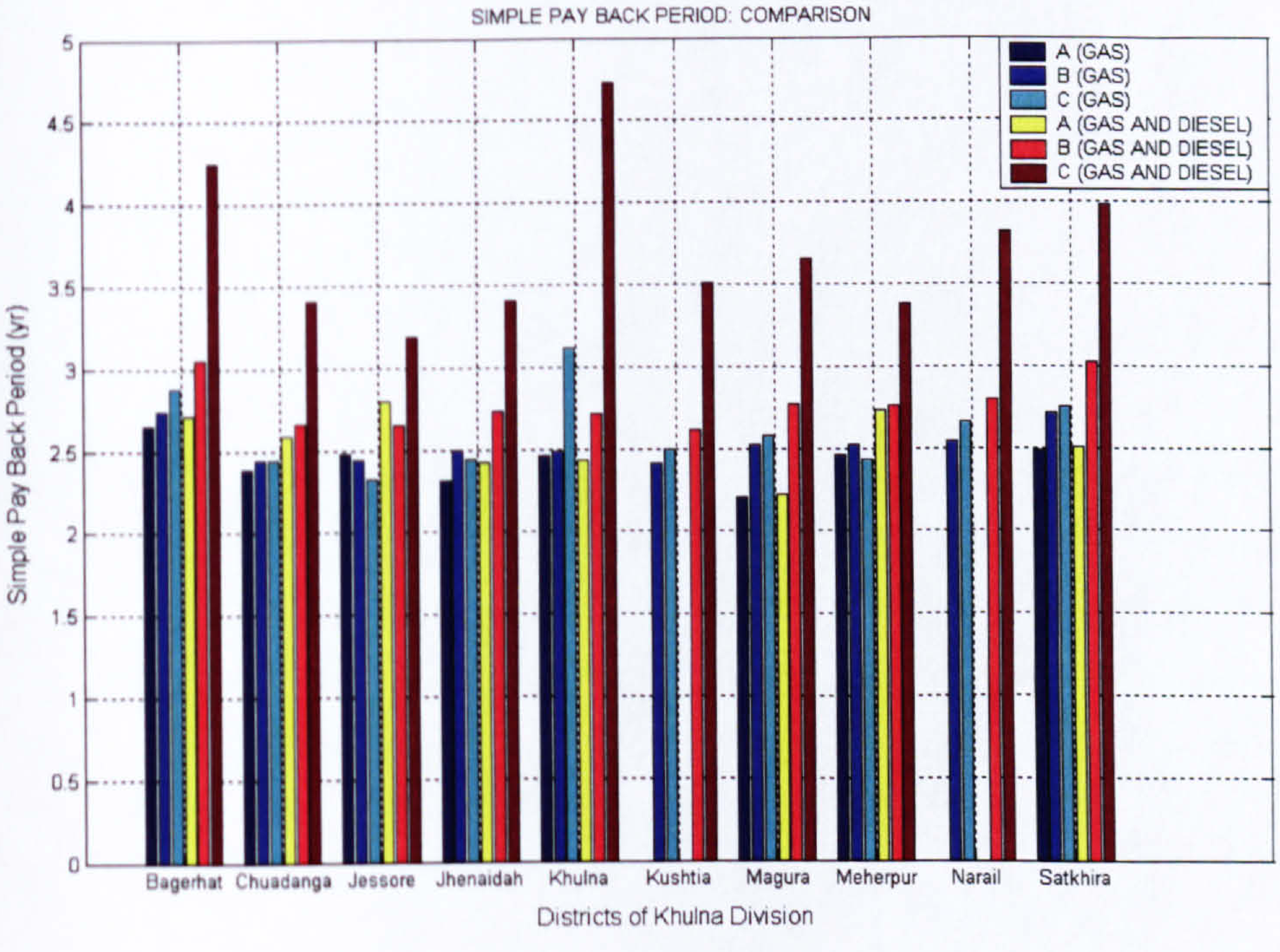


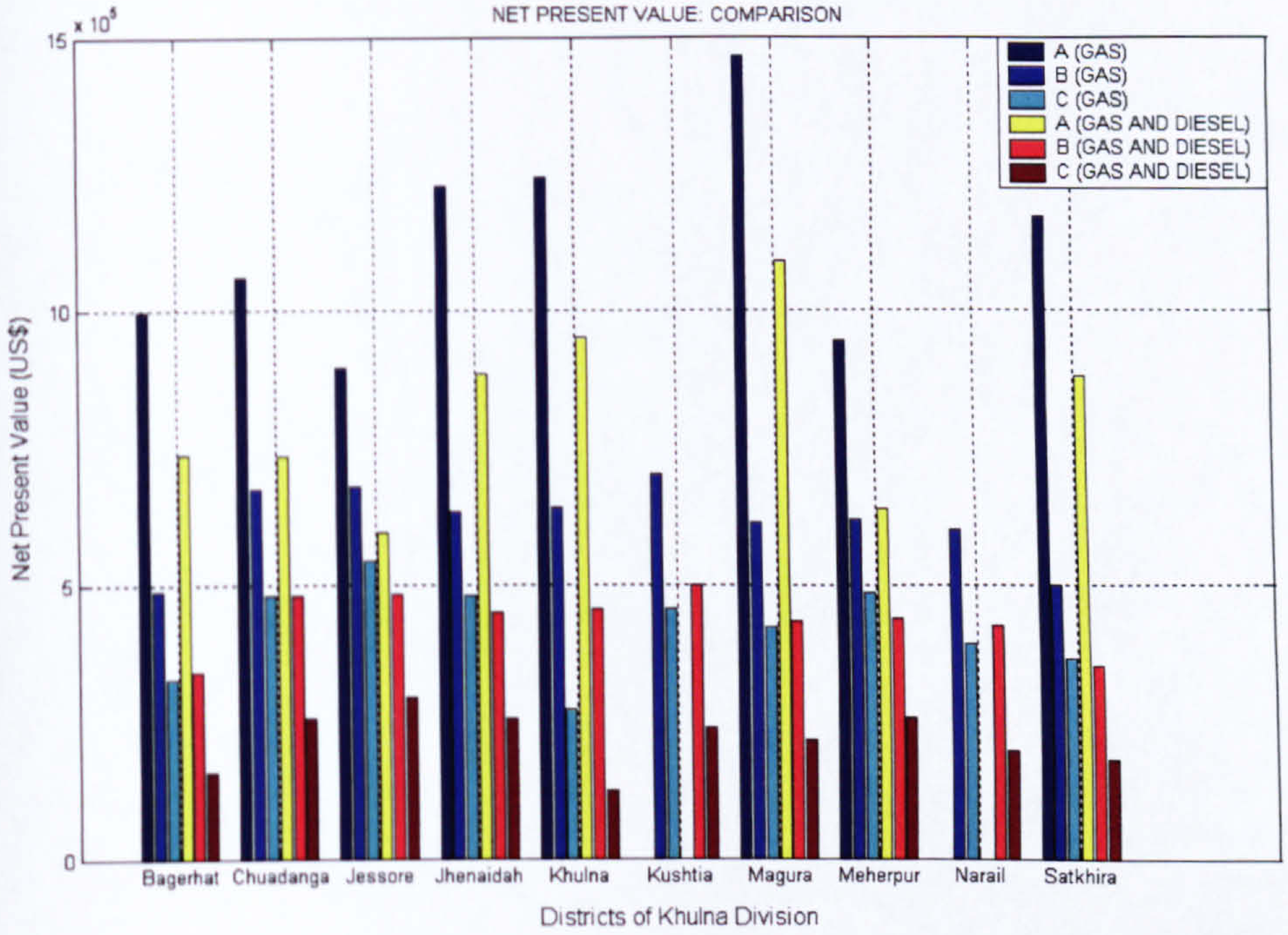
E1.3 Plant Sizing and Economics

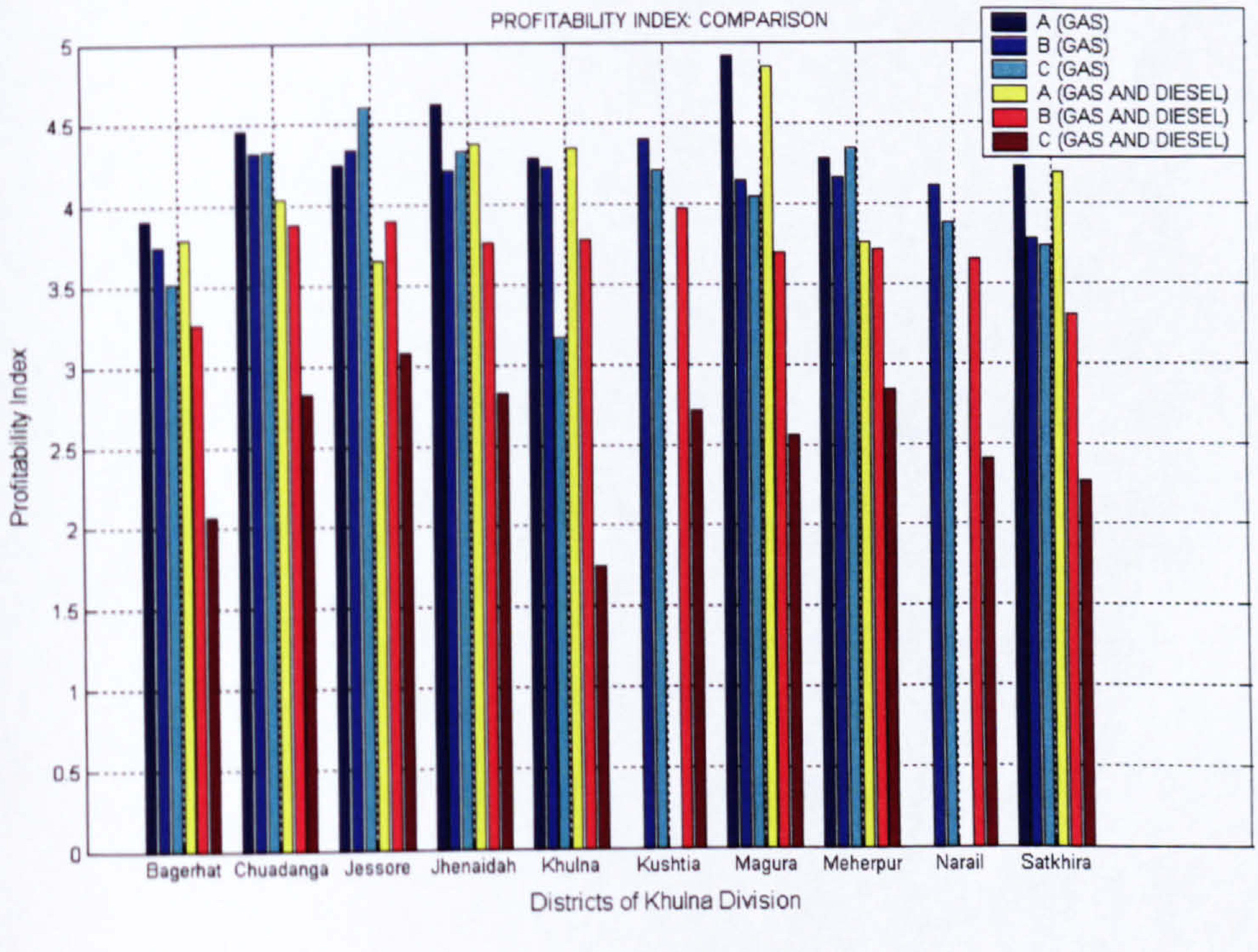




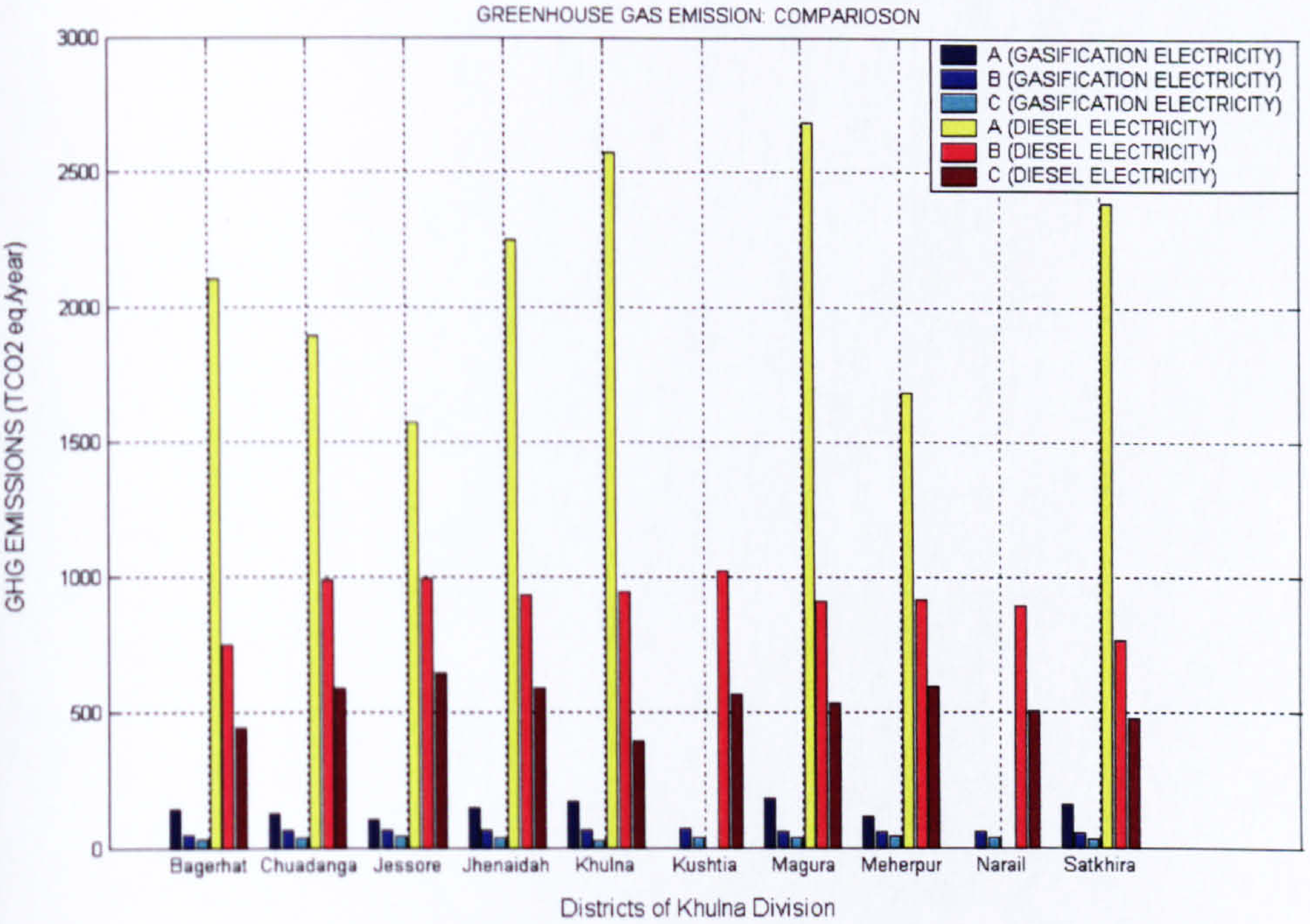

COST OF ELECTRICITY GENERATION: COMPARIOSON
Cost of Electricity Generation (US$/kWh)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
A (GAS)
B (GAS)
C (GAS)
A (DIESEL)
B (DIESEL)
C (DIESEL)
A (GAS AND DIESEL)
B (GAS AND DIESEL)
C (GAS AND DIESEL)
Bagerhat
Chuadanga
Jessore
Jhenaidah
Khulna
Kushtia
Magura
Meherpur
Narail
Satkhira
Districts of Khulna Division


SIMPLE PAY BACK PERIOD: COMPARISON
Simple Pay Back Period (yr)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
A (GAS)
B (GAS)
C (GAS)
A (GAS AND DIESEL)
B (GAS AND DIESEL)
C (GAS AND DIESEL)
Bagerhat
Chuadanga
Jessore
Jhenaidah
Khulna
Kushtia
Magura
Meherpur
Narail
Satkhira
Districts of Khulna Division


NET PRESENT VALUE: COMPARISON
x 10^5
15
10
5
0
Net Present Value (US$)
A (GAS)
B (GAS)
C (GAS)
A (GAS AND DIESEL)
B (GAS AND DIESEL)
C (GAS AND DIESEL)
Bagerhat
Chuadanga
Jessore
Jhenaidah
Khulna
Kushtia
Magura
Meherpur
Narail
Satkhira
Districts of Khulna Division


PROFITABILITY INDEX: COMPARISON
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Profitability Index
A (GAS)
B (GAS)
C (GAS)
A (GAS AND DIESEL)
B (GAS AND DIESEL)
C (GAS AND DIESEL)
Bagerhat
Chuadanga
Jessore
Jhenaidah
Khulna
Kushtia
Magura
Meherpur
Narail
Satkhira
Districts of Khulna Division

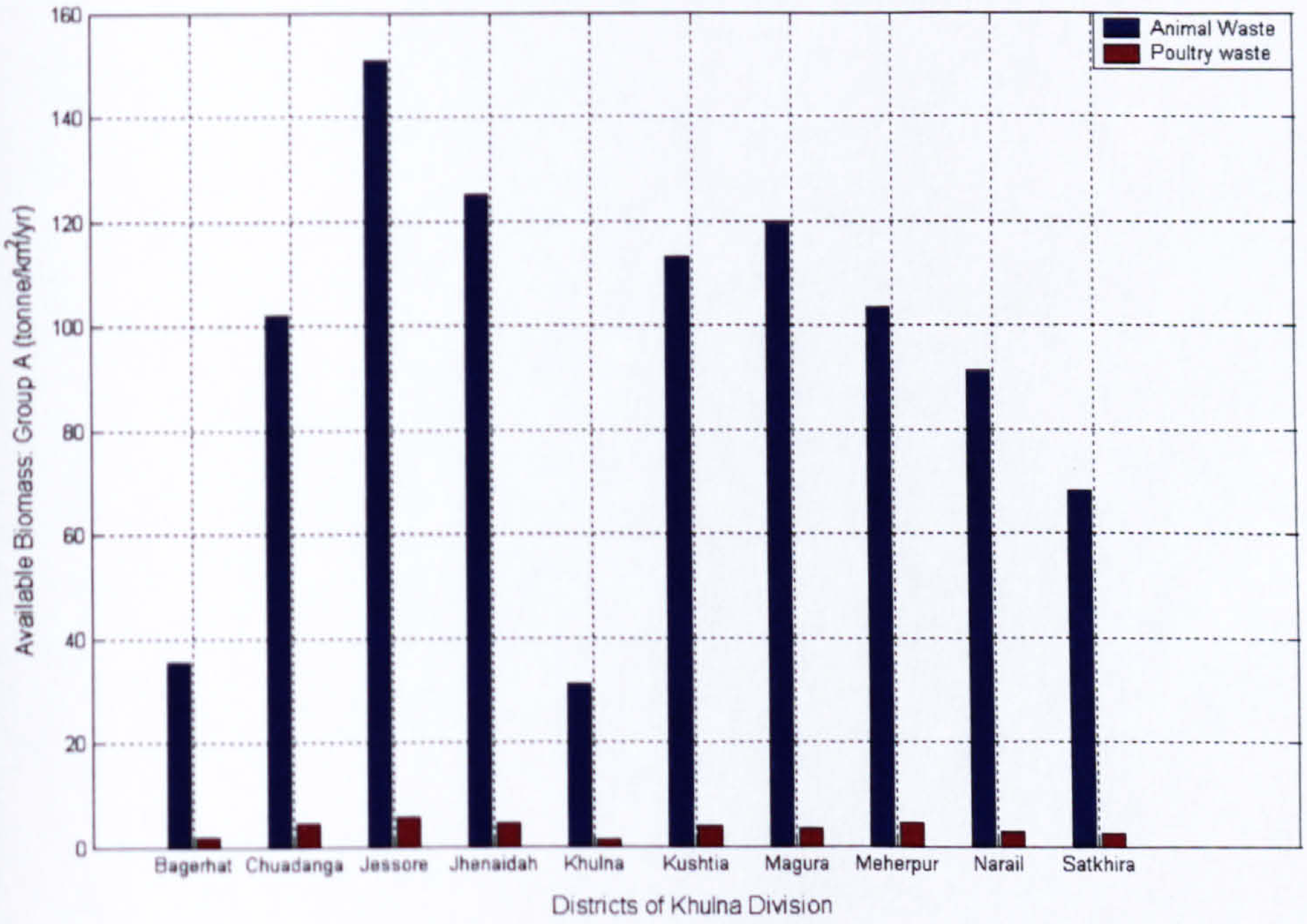
E1.4 GHG Emissions Savings Potential

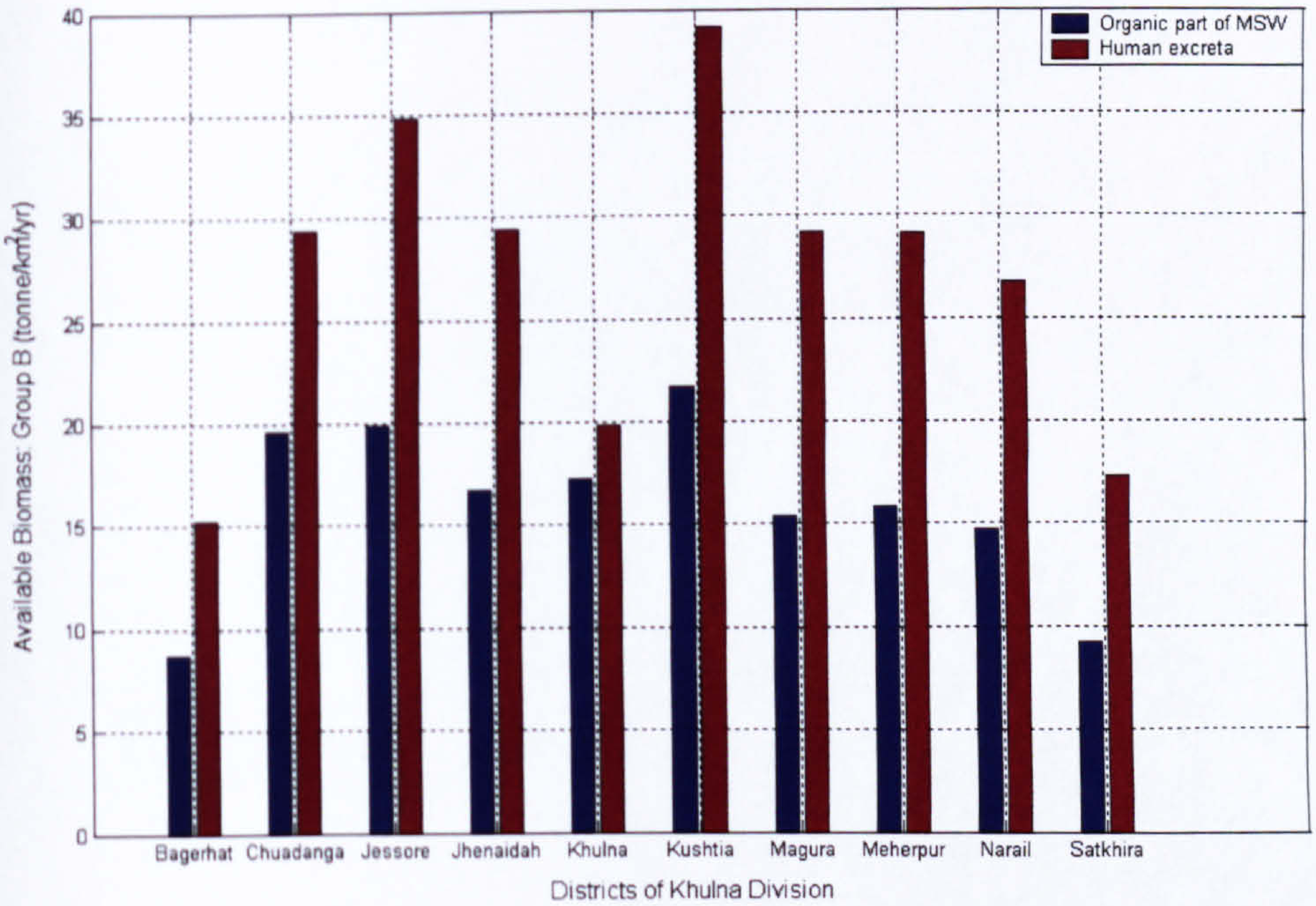


E2 Anaerobic Digestion Electricity

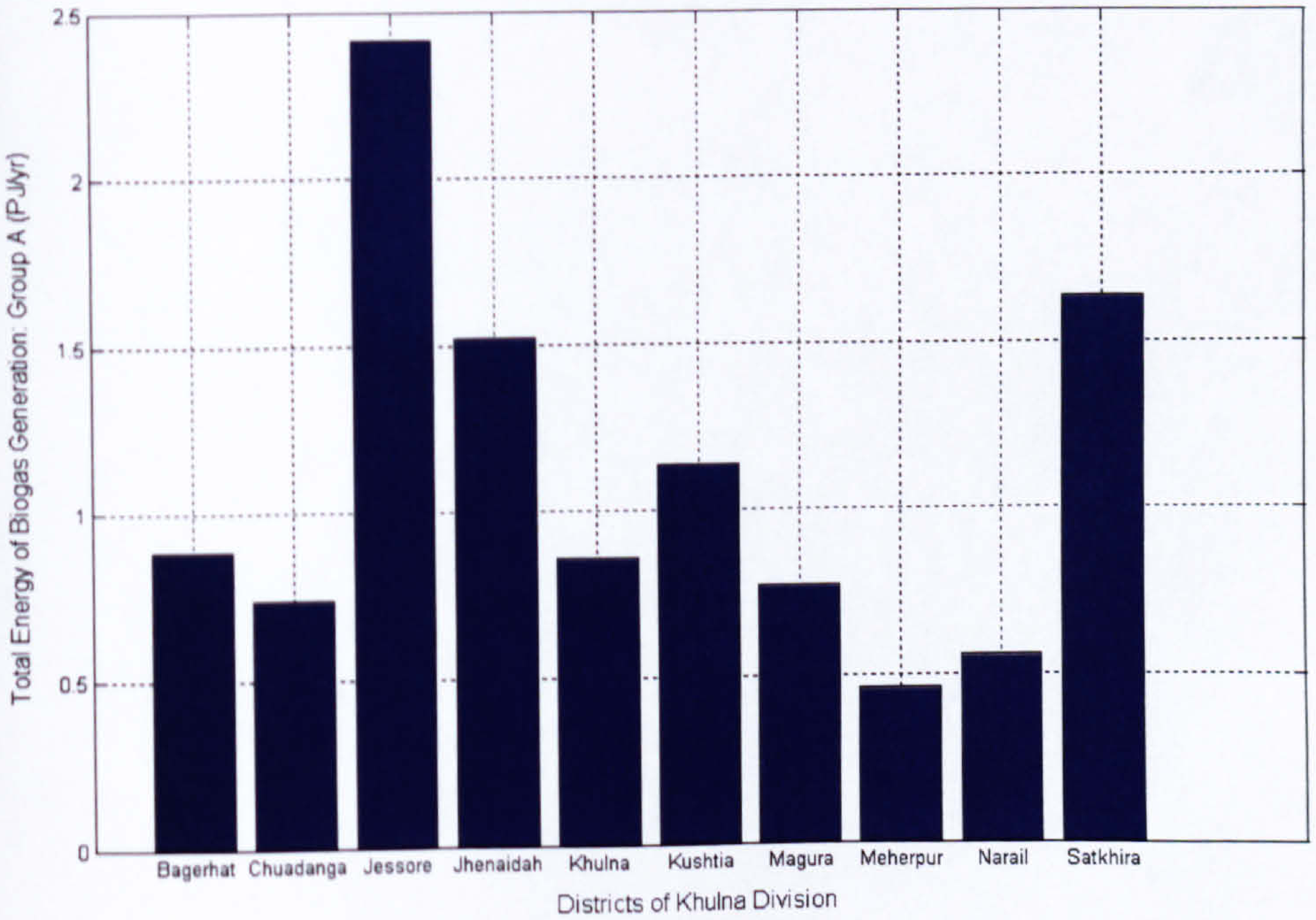
Group A: Animal wastes and poultry wastes
Group B; Organic part of MSW and Human excreta

E2.1 Biomass Availability

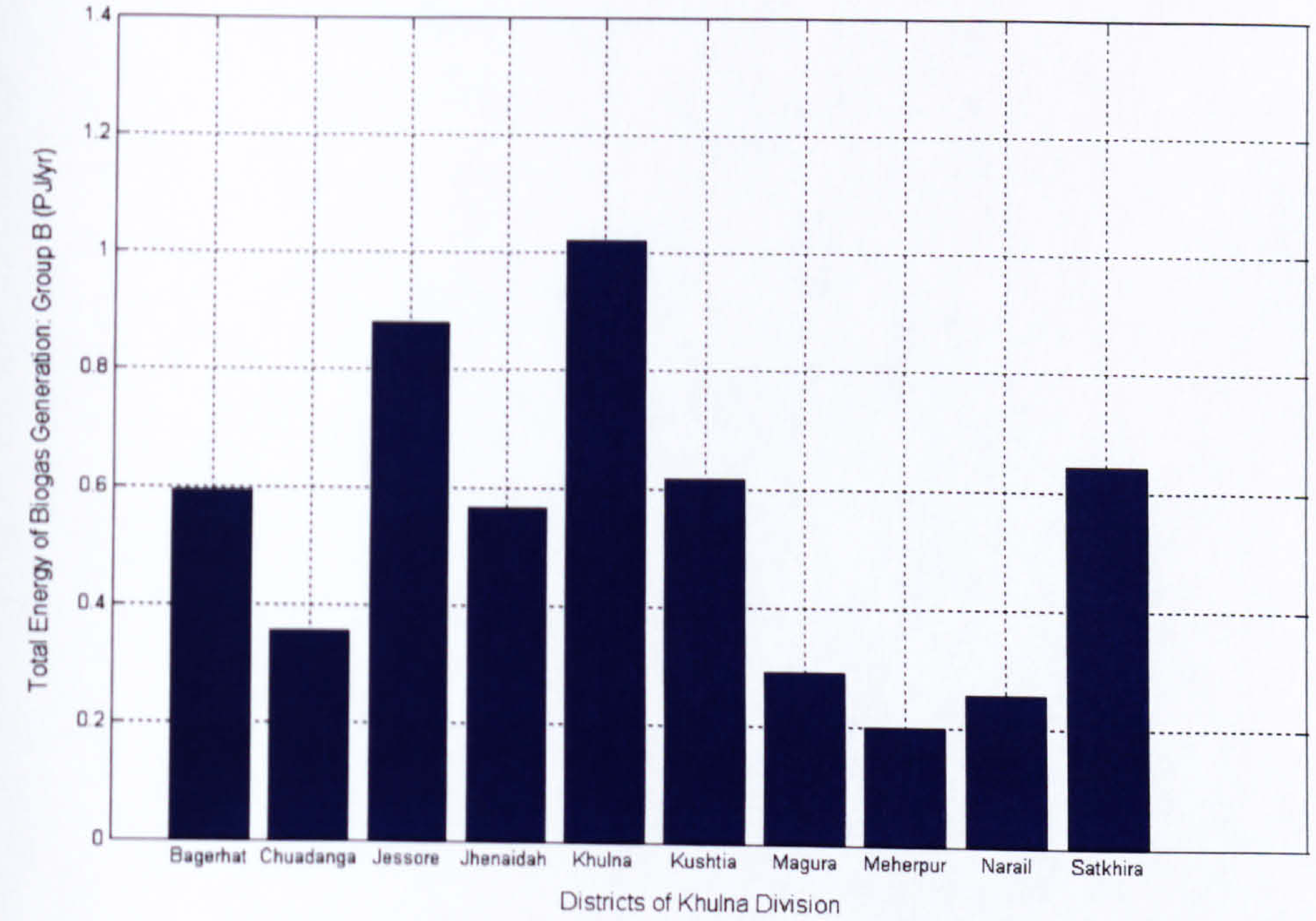




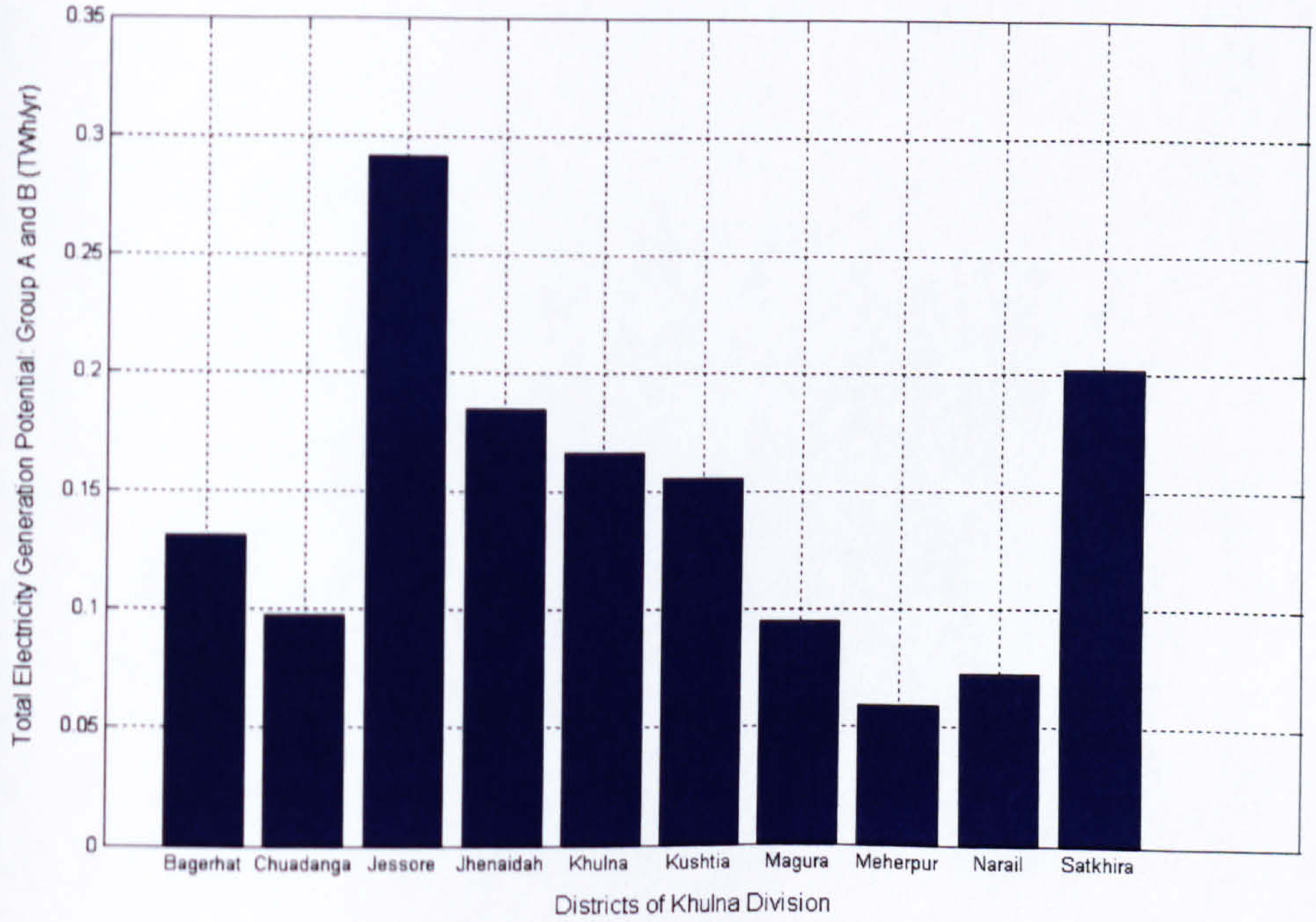
Organic part of MSW
Human excreta
Available Biomass: Group B (tonne/km²/yr)
0
5
10
15
20
25
30
35
40
Bagerhat
Chuadanga
Jessore
Jhenaidah
Khulna
Kushtia
Magura
Meherpur
Narail
Satkhira
Districts of Khulna Division



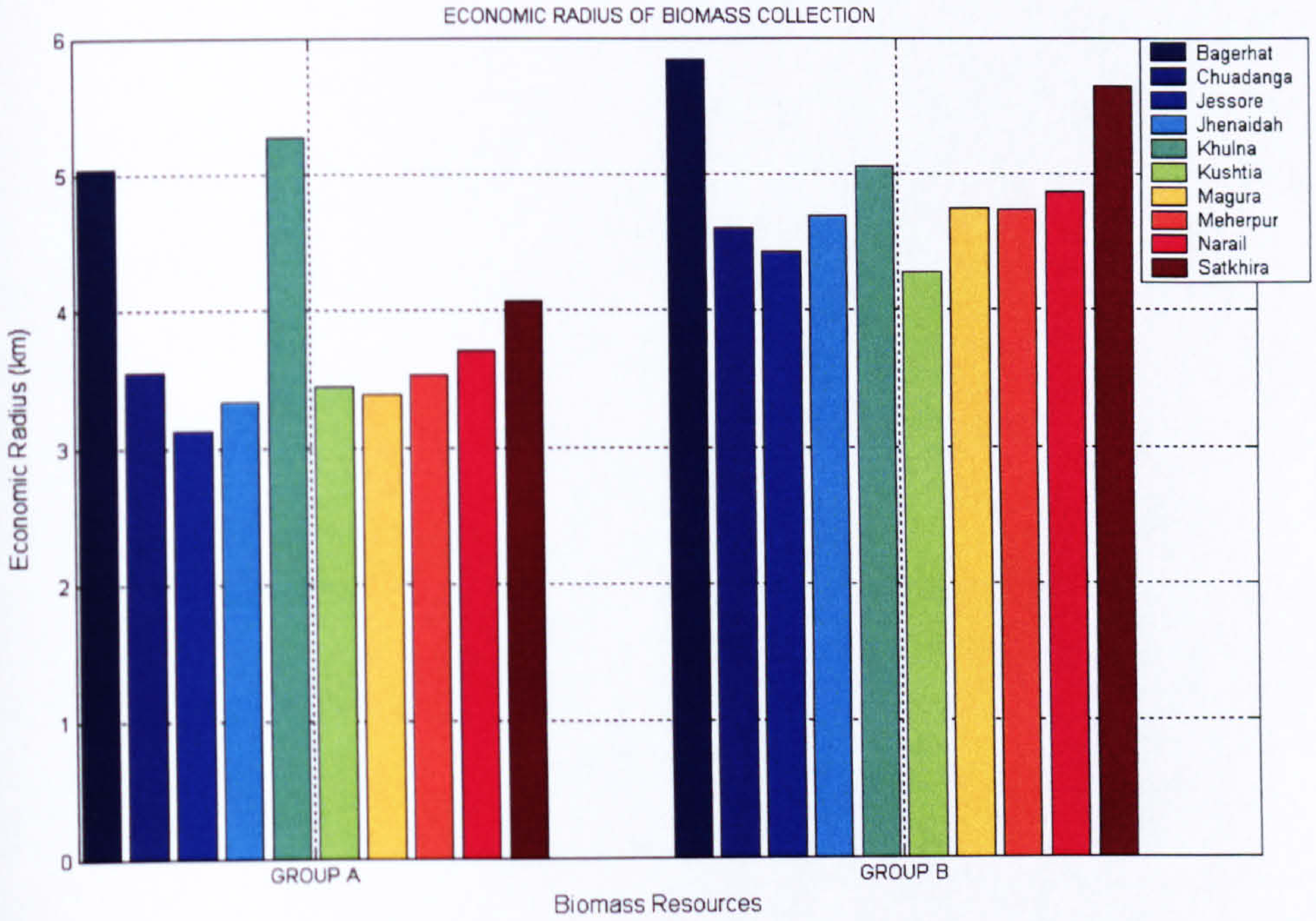
Total Energy of Biogas Generation: Group A (PJ/yr)
0
0.5
1
1.5
2
2.5
Bagerhat
Chuadanga
Jessore
Jhenaidah
Khulna
Kushtia
Magura
Meherpur
Narail
Satkhira
Districts of Khulna Division

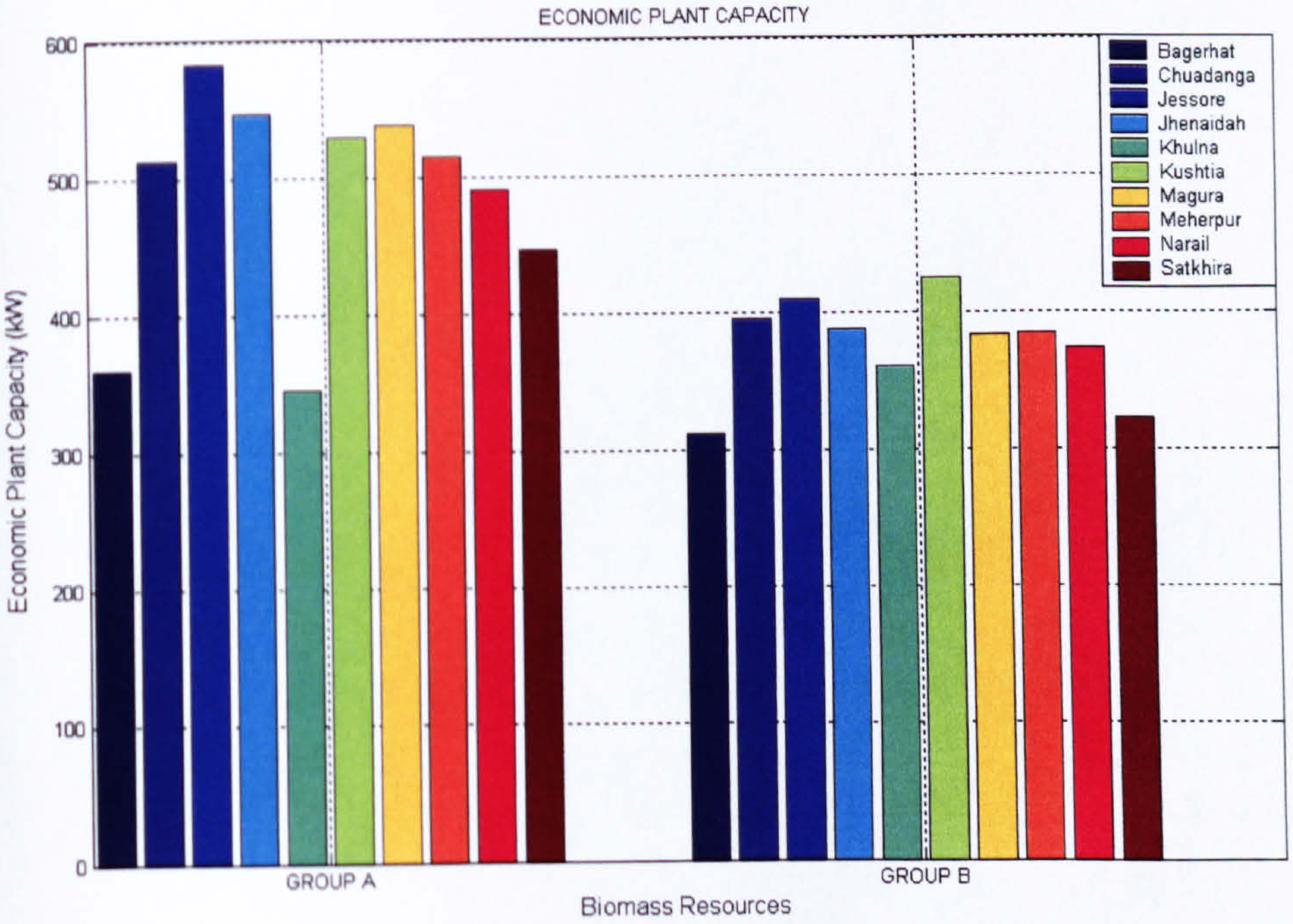


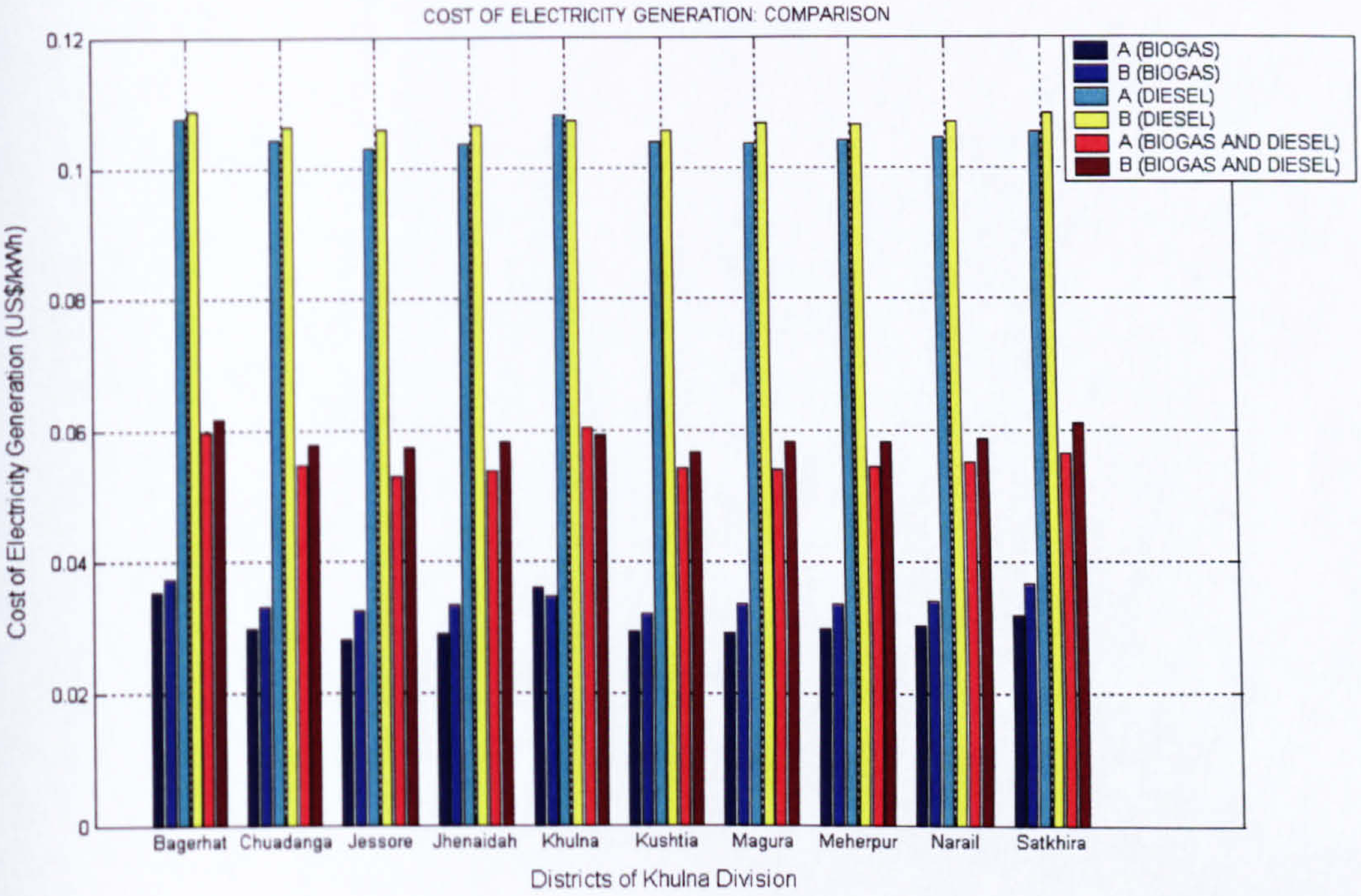
E2.2 Total Electricity Generation Potential

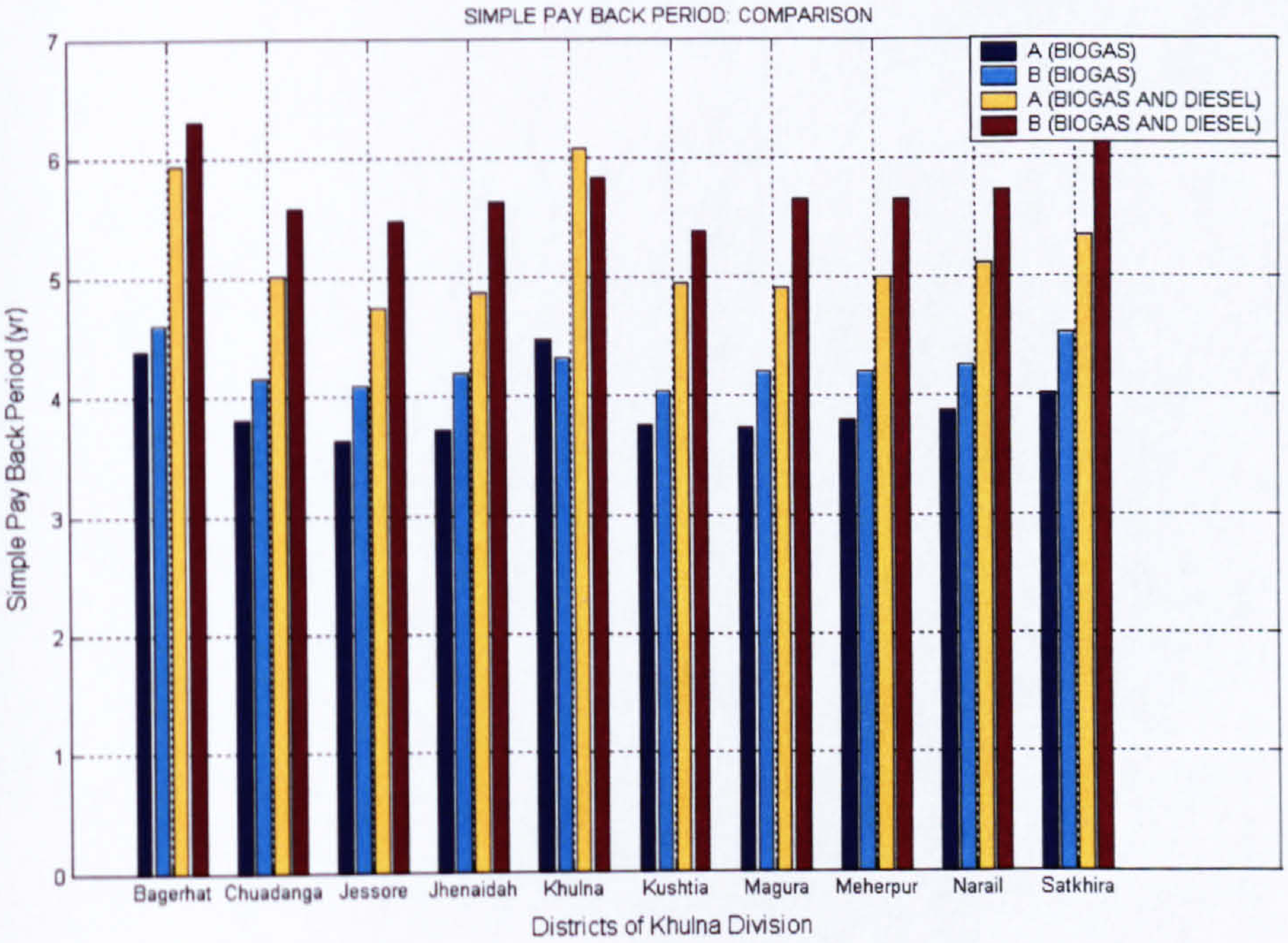


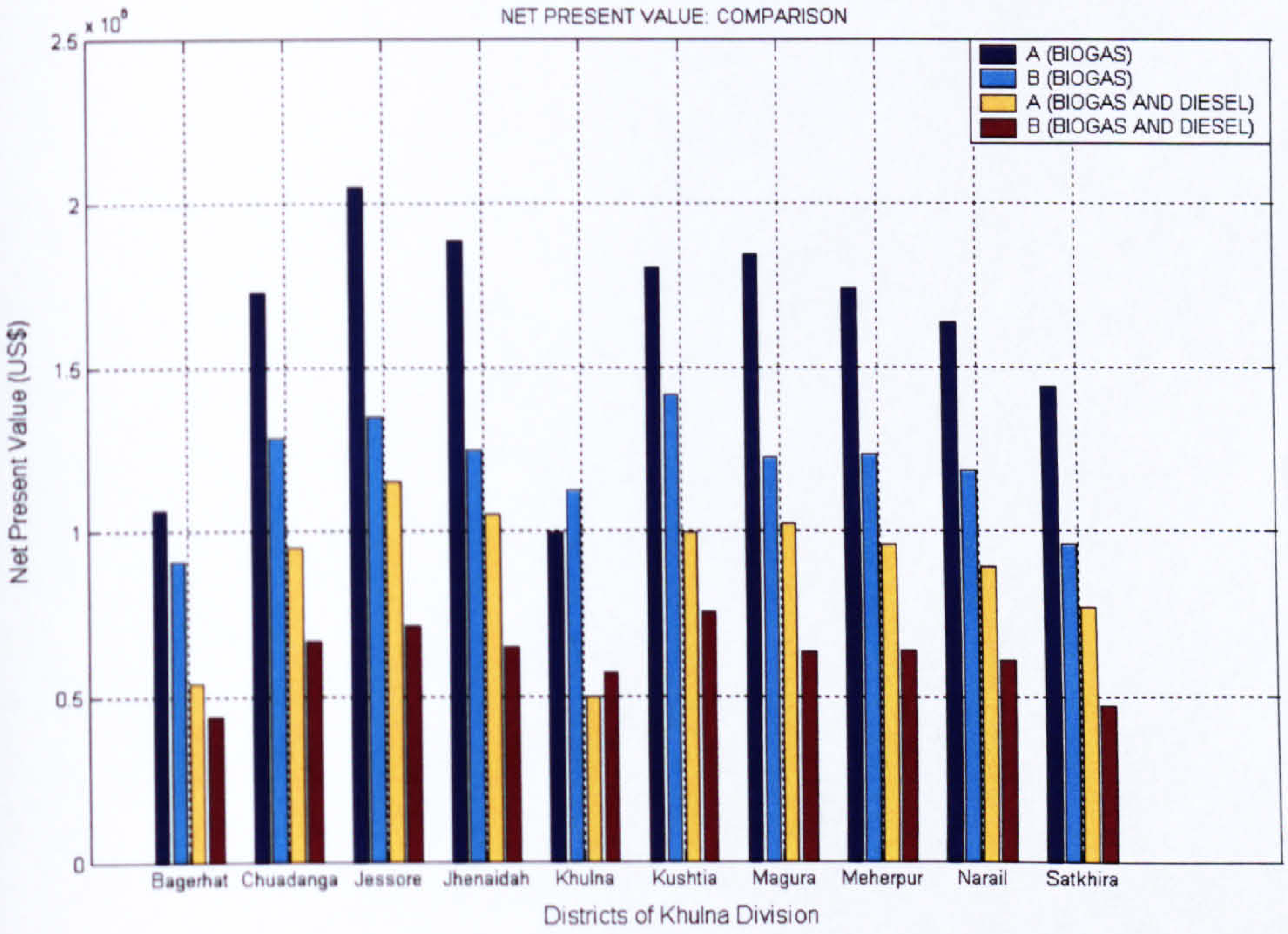
E2.3 Plant Sizing and Economics

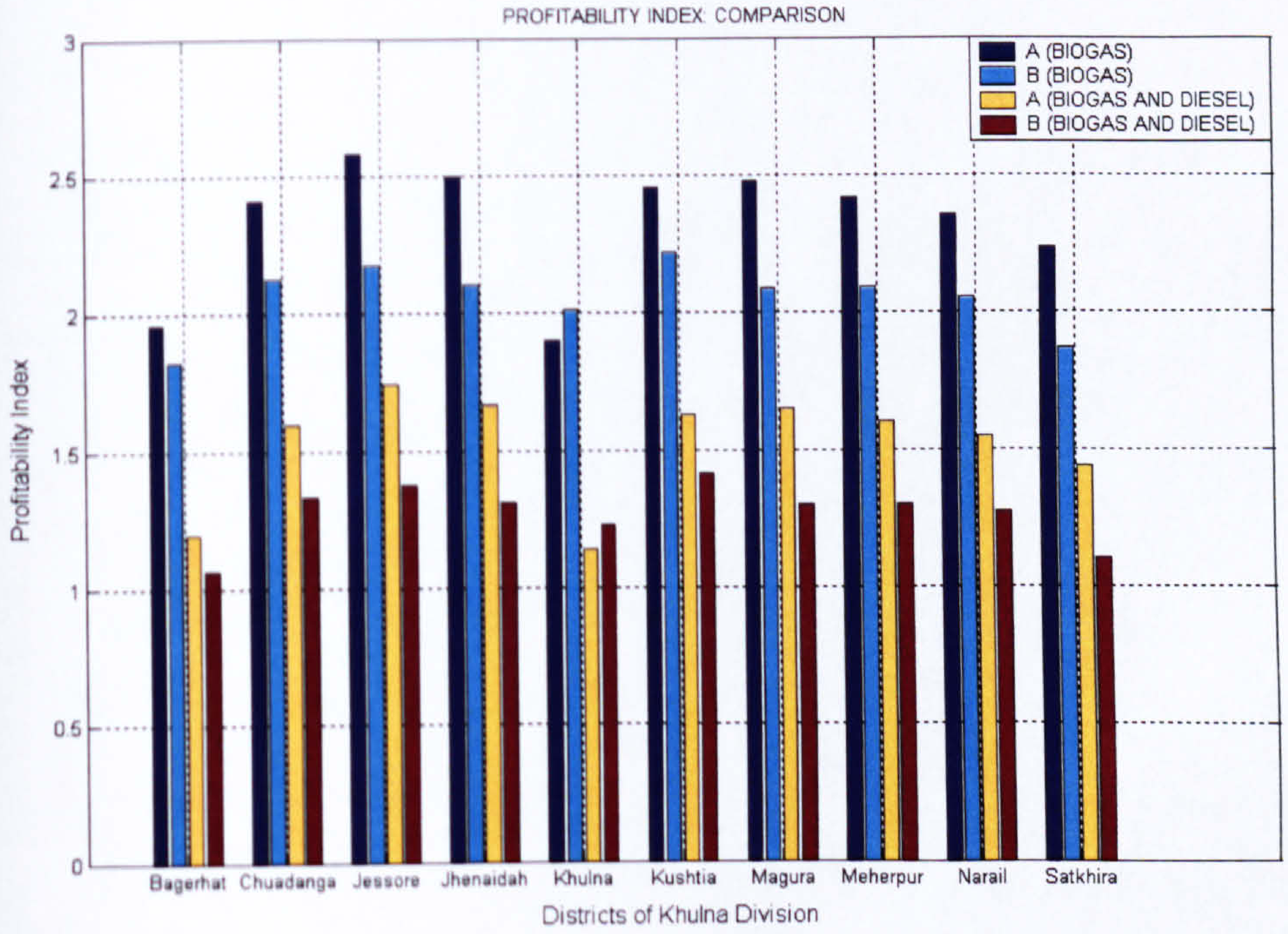




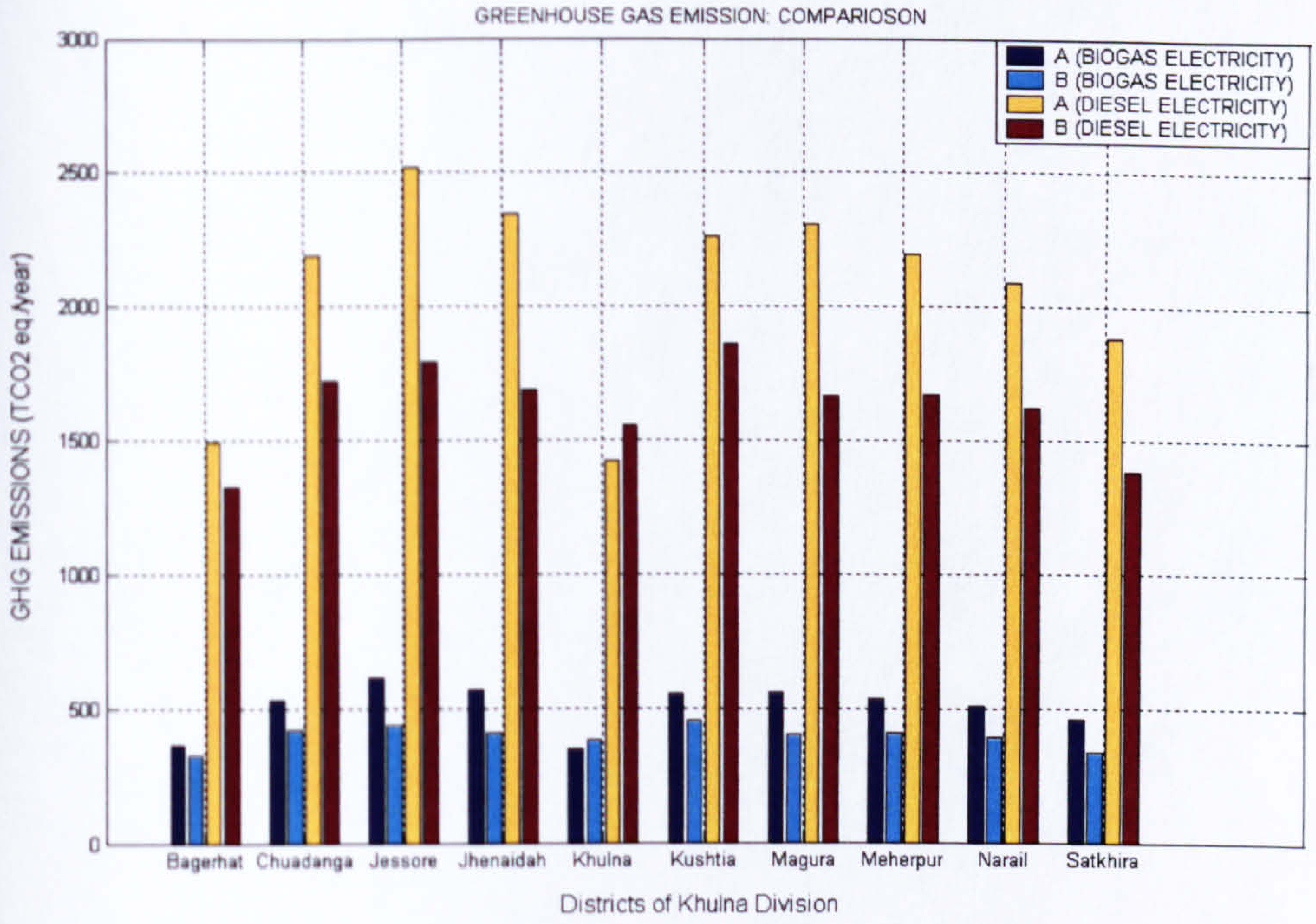

COST OF ELECTRICITY GENERATION: COMPARISON
Cost of Electricity Generation (US$/kWh)
0
0.02
0.04
0.06
0.08
0.1
0.12
Districts of Khulna Division
Bagerhat
Chuadanga
Jessore
Jhenaidah
Khulna
Kushtia
Magura
Meherpur
Narail
Satkhira
A (BIOGAS)
B (BIOGAS)
A (DIESEL)
B (DIESEL)
A (BIOGAS AND DIESEL)
B (BIOGAS AND DIESEL)


SIMPLE PAY BACK PERIOD: COMPARISON
Simple Pay Back Period (yr)
0
1
2
3
4
5
6
7
Districts of Khulna Division
Bagerhat
Chuadanga
Jessore
Jhenaidah
Khulna
Kushtia
Magura
Meherpur
Narail
Satkhira
A (BIOGAS)
B (BIOGAS)
A (BIOGAS AND DIESEL)
B (BIOGAS AND DIESEL)


NET PRESENT VALUE: COMPARISON
x 10^6
Net Present Value (US$)
2.5
2
1.5
1
0.5
0
A (BIOGAS)
B (BIOGAS)
A (BIOGAS AND DIESEL)
B (BIOGAS AND DIESEL)
Bagerhat
Chuadanga
Jessore
Jhenaidah
Khulna
Kushtia
Magura
Meherpur
Narail
Satkhira
Districts of Khulna Division


PROFITABILITY INDEX: COMPARISON
Profitability Index
3
2.5
2
1.5
1
0.5
0
A (BIOGAS)
B (BIOGAS)
A (BIOGAS AND DIESEL)
B (BIOGAS AND DIESEL)
Bagerhat
Chuadanga
Jessore
Jhenaidah
Khulna
Kushtia
Magura
Meherpur
Narail
Satkhira
Districts of Khulna Division

E2.4 GHG Emissions Savings Potential



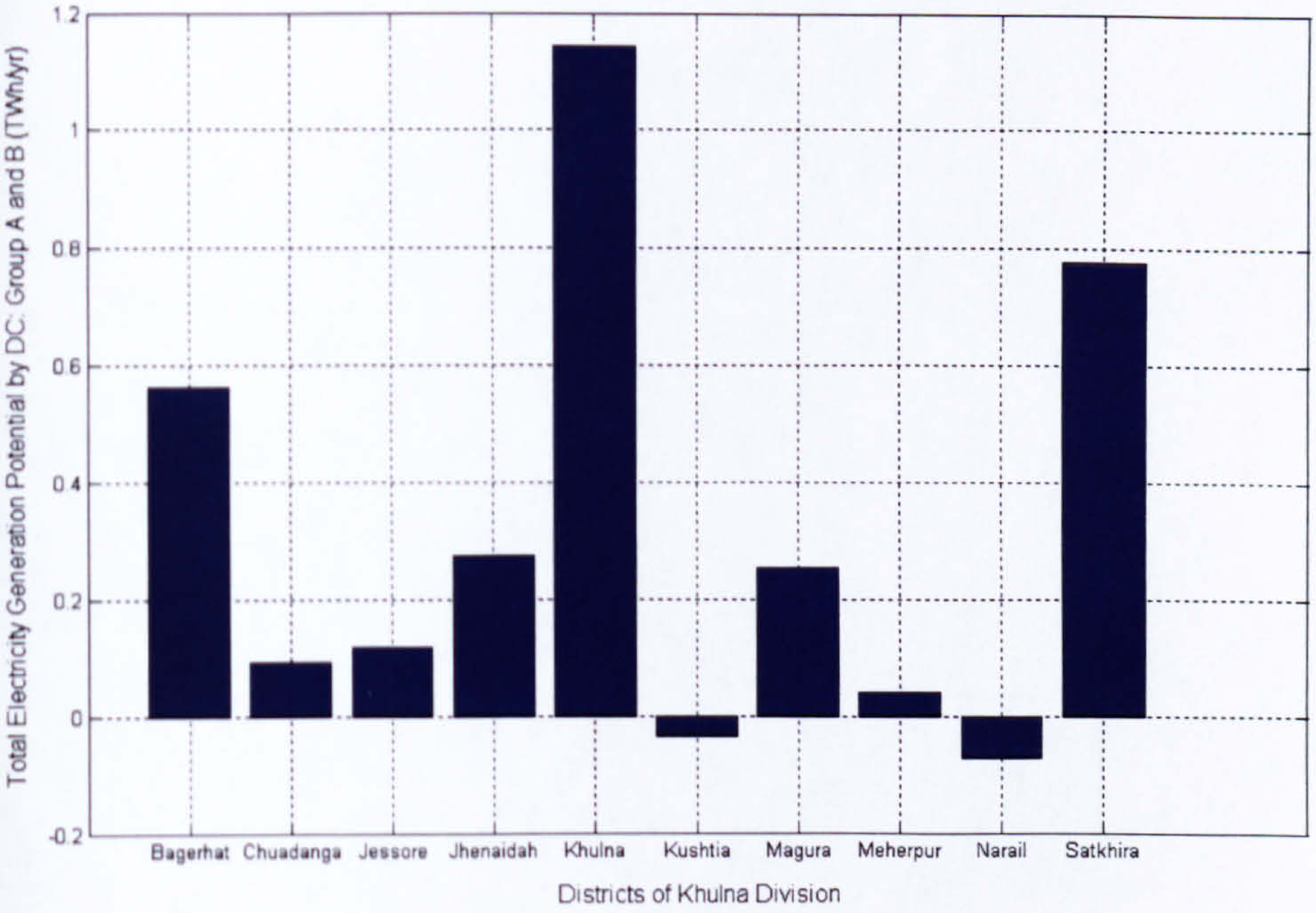
E3 Direct Combustion Electricity

Group A: Agricultural wastes and forestry residues
Group B; Gasifiable/Combustible parts of MSW

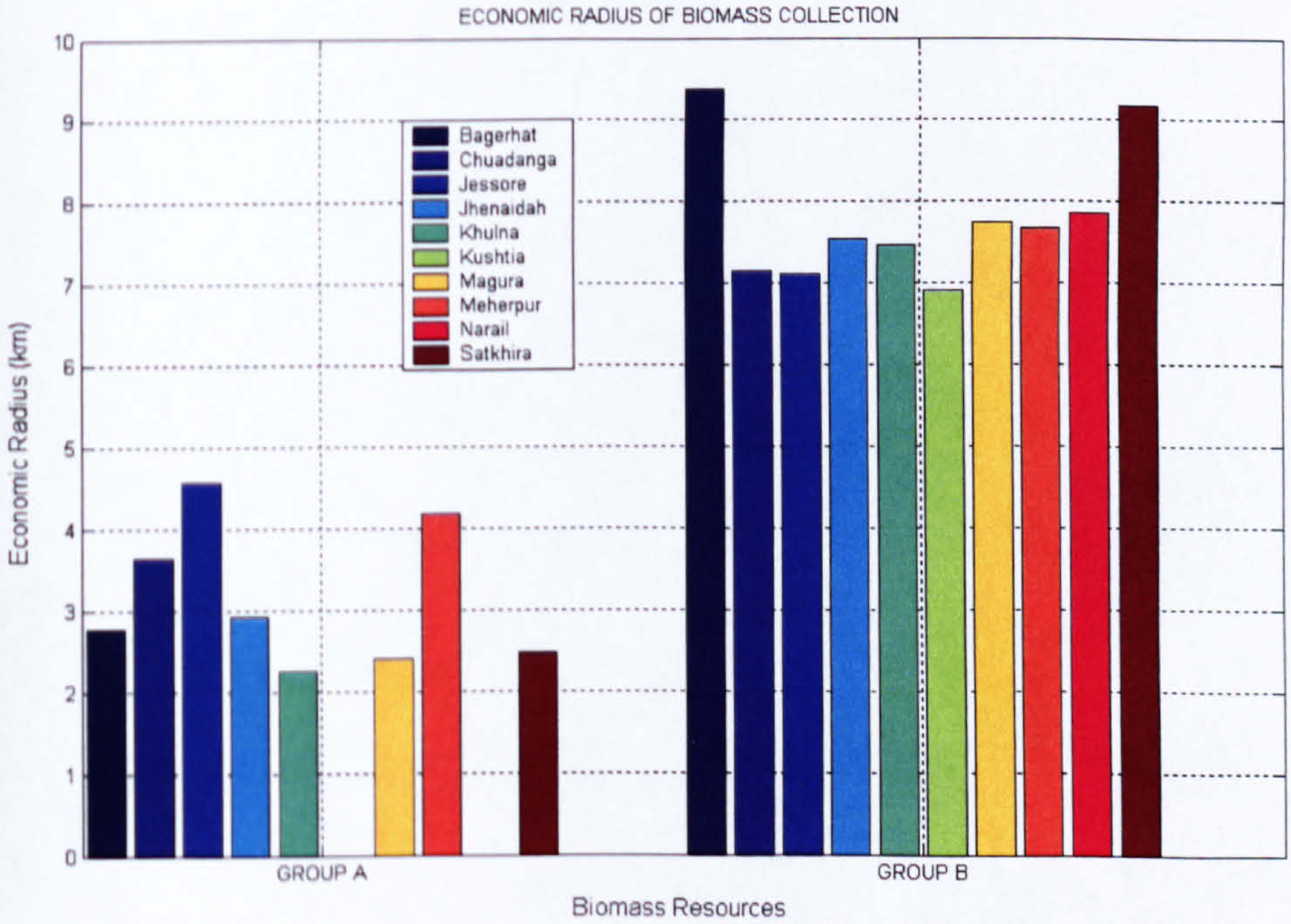
E3.1 Biomass Availability

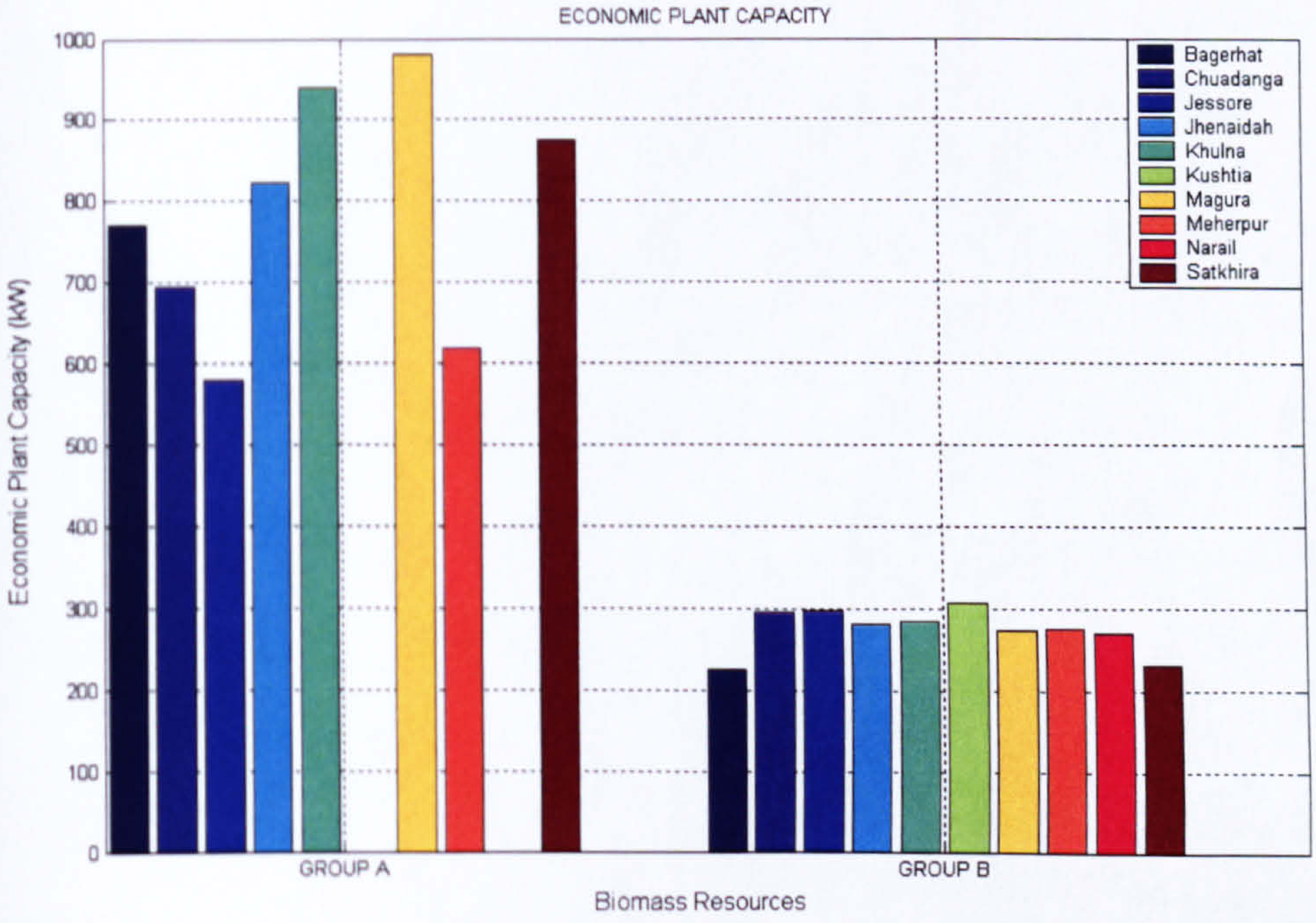
Biomass availability is same as for gasification (see E1.1).

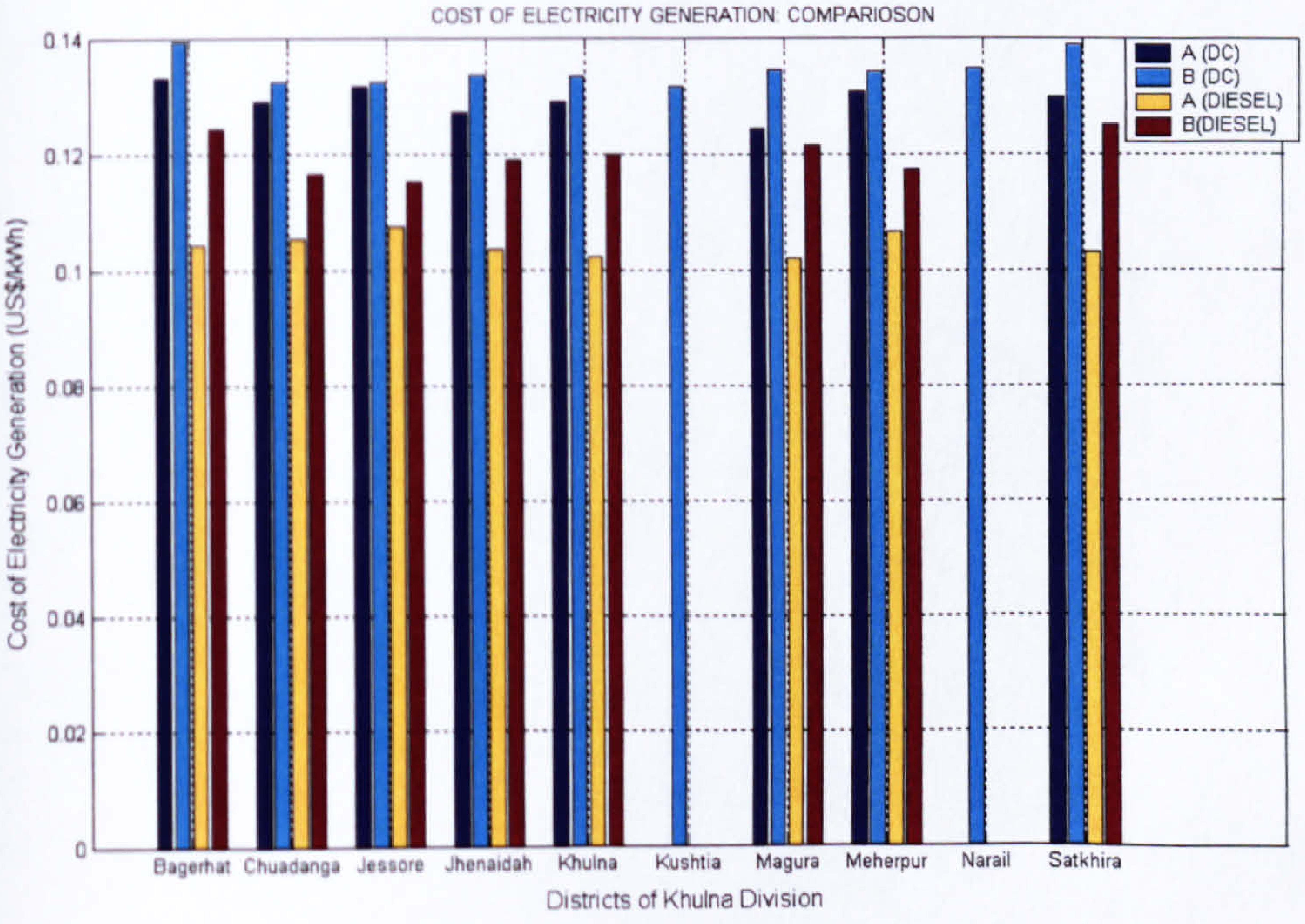
E3.2 Total Electricity Generation Potential

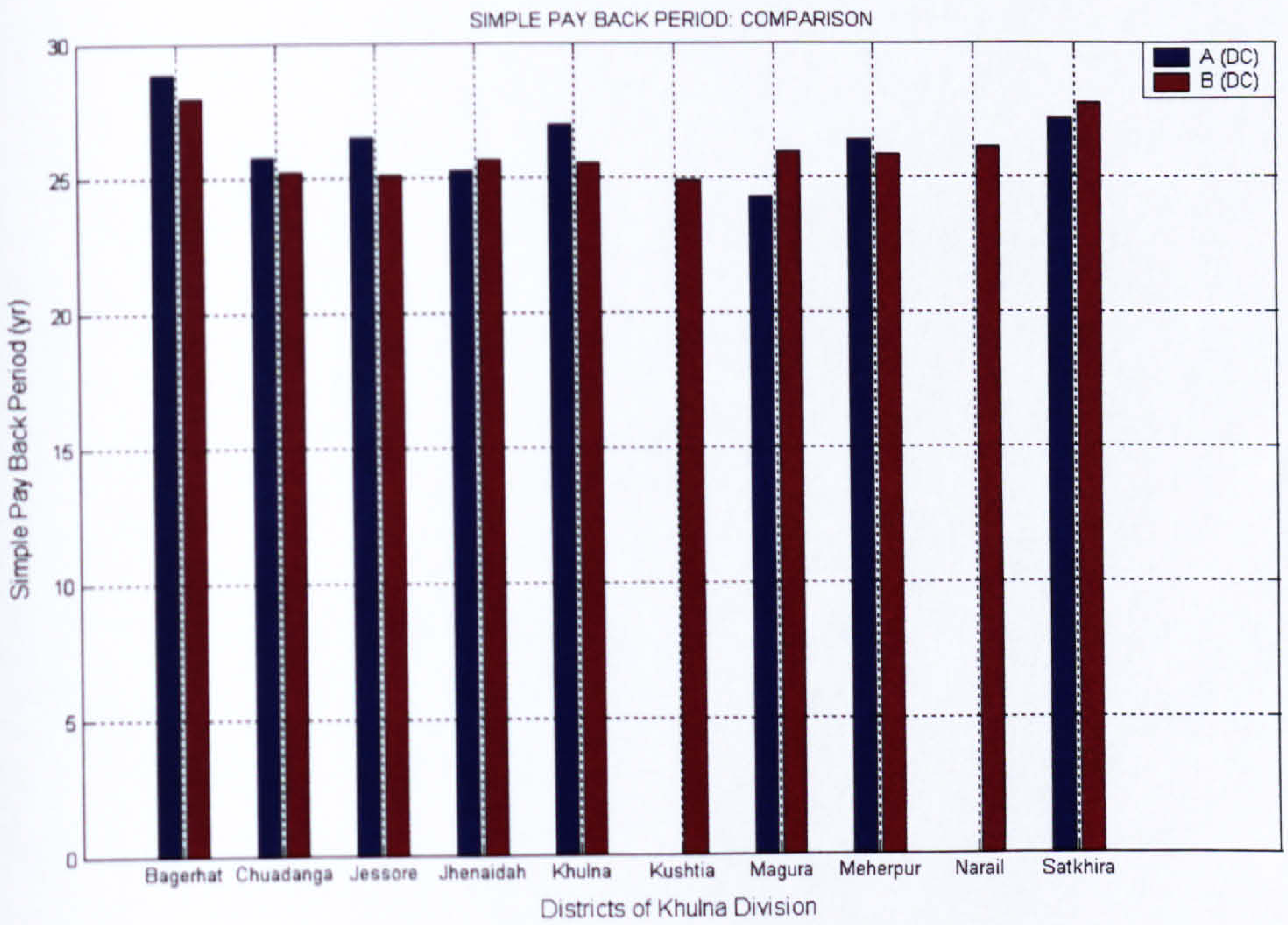


E3.3 Plant Sizing and Economics

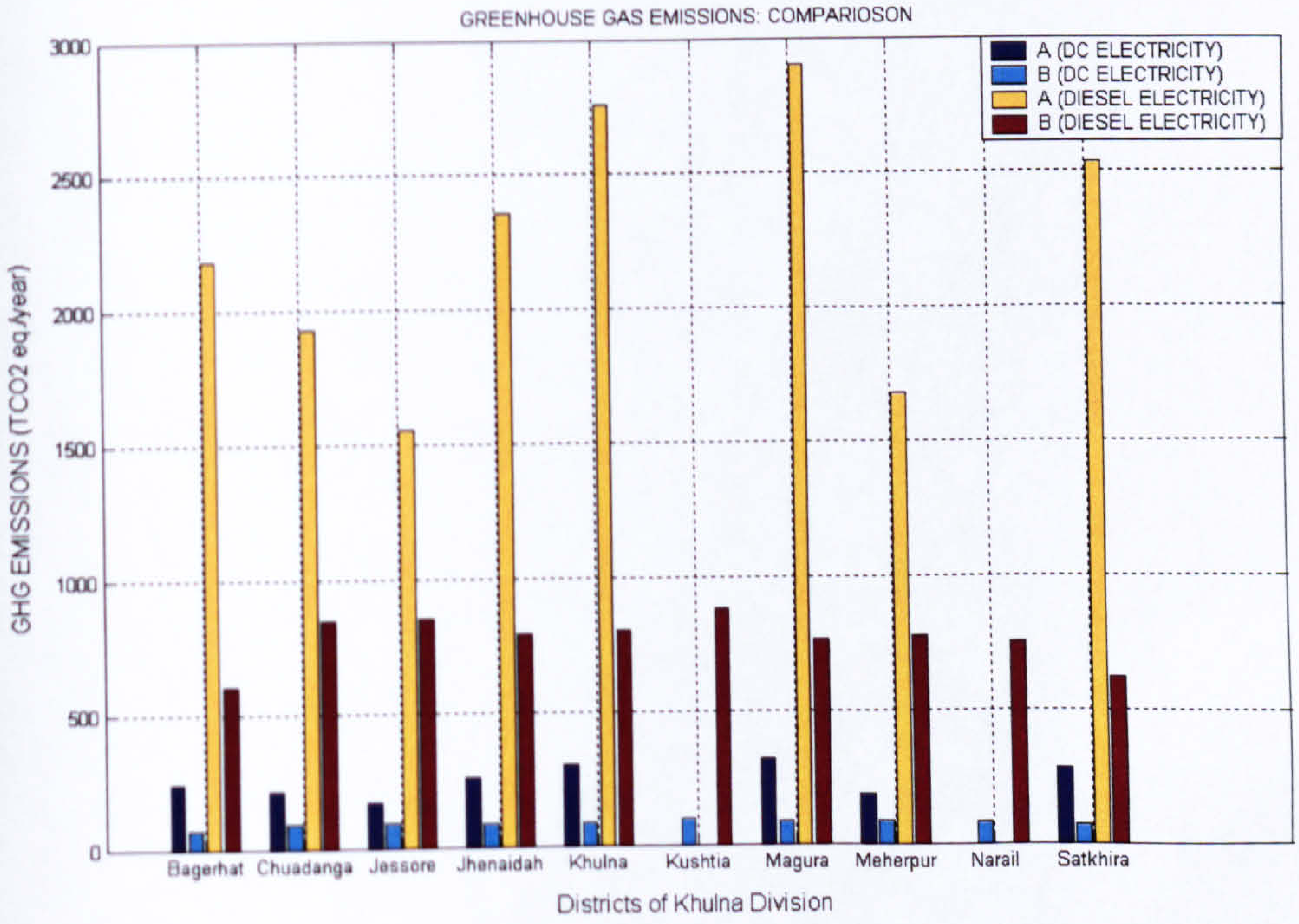



ECONOMIC PLANT CAPACITY
Economic Plant Capacity (kW)
0
100
200
300
400
500
600
700
800
900
1000
GROUP A
GROUP B
Biomass Resources
Bagerhat
Chuadanga
Jessore
Jhenaidah
Khulna
Kushtia
Magura
Meherpur
Narail
Satkhira


COST OF ELECTRICITY GENERATION: COMPARIOSON
Cost of Electricity Generation (US$/kWh)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Bagerhat
Chuadanga
Jessore
Jhenaidah
Khulna
Kushtia
Magura
Meherpur
Narail
Satkhira
Districts of Khulna Division
A (DC)
B (DC)
A (DIESEL)
B(DIESEL)



E3.4 GHG Emissions Savings Potential



APPENDIX F
RESULTS: DIVISION-WISE

Name of the Division	Availability of biomass for electricity generation (ktonne dry matter)					
	Agricultural wastes and forestry residues	MSW		Animal wastes	Poultry wastes	Human excreta
		Gasifiyable/ Combustible	Organic fraction			
Barisal	-440.61	70.61	176.54	940.37	62.13	312.50
Chittagong	4584.69	221.68	554.20	1486.96	118.67	884.38
Dhaka	-2240.35	385.72	964.30	2709.72	127.50	1397.85
Khulna	2848.38	132.00	329.99	1765.05	67.50	537.45
Rajshahi	12396.90	254.72	636.79	4179.45	150.63	1114.99
Sylhet	-150.51	63.45	158.63	811.54	32.01	289.41

Table F1 Division wise annual biomass availability for electricity generation: by source

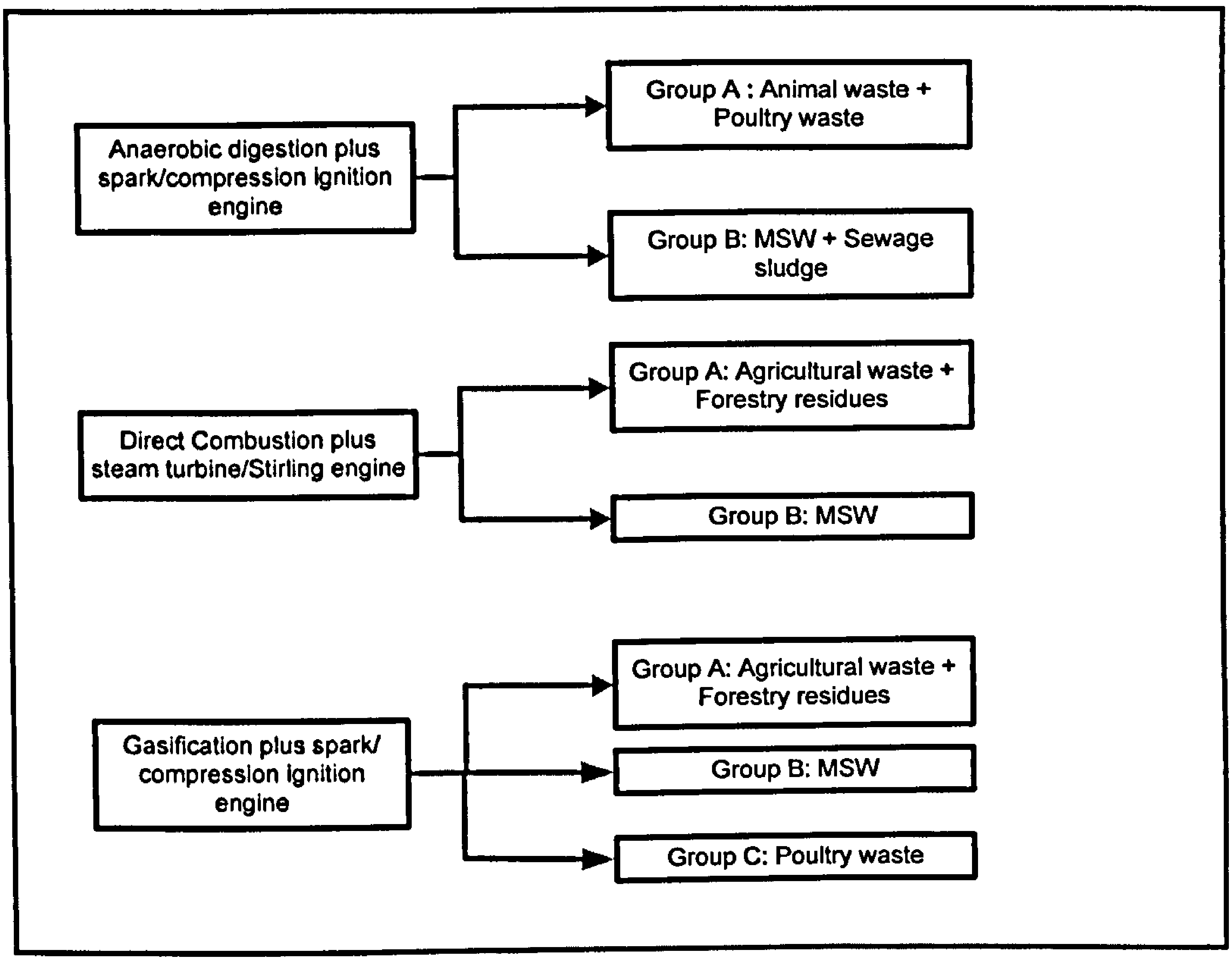


Table F2 Feasible technology and biomass resources

Name of the Division	Type of Technology													
	Gasification Technology						Anaerobic Digestion Technology				Direct Combustion Technology			
	Biomass availability (PJ)			Electricity generation potential (TWh)			Biomass availability[a] (PJ)		Electricity generation potential (TWh)		Biomass availability (PJ)		Electricity generation potential (TWh)	
	Group A	Group B	Group C	Group A	Group B	Group C	Group A	Group B	Group A	Group B	Group A	Group B	Group A	Group B
Barisal	-6.57	1.31	0.84	-0.30	0.06	0.04	6.02	3.06	0.53	0.27	-6.57	1.31	-0.45	0.07
Chittagong	70.51	4.11	1.60	3.26	0.19	0.07	9.63	9.01	0.85	0.80	70.51	4.11	4.78	0.23
Dhaka	-32.92	7.16	1.72	-1.52	0.33	0.08	17.02	14.79	1.51	1.31	-32.92	7.16	-2.23	0.40
Khulna	44.53	2.45	0.91	2.06	0.11	0.04	11.00	5.43	0.97	0.48	44.53	2.45	3.02	0.14
Rajshahi	207.34	4.73	2.03	9.59	0.22	0.09	25.98	10.97	2.30	0.97	207.34	4.73	14.05	0.26
Sylhet	-1.94	1.18	0.43	-0.09	0.05	0.02	5.06	2.80	0.45	0.25	-1.94	1.18	-0.13	0.07

[a] energy potential is estimated as energy of biogas generated.

Table F3 Division wise annual biomass energy availability and electricity generation potential: by technology