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Md. Alam Hossain Mondal

Implications of renewable energy technologies in the Bangladesh power sector: long-term planning strategies

ABSTRACT

Bangladesh is facing daunting energy challenges: Security concerns over growing fuel imports, limited domestic energy resources for power generation, and projected demands for electricity that will exceed domestic supply capabilities within a few years. By acknowledging the potential of renewable energy resources, the country could possibly meet its unprecedented energy demand, thus increasing electricity accessibility for all and enhancing energy security through their advancement. The integration of renewable energy technologies in the power sector through national energy planning would, therefore, be a step in the right direction, not only for sustainable development of the country but also as part of Bangladesh's responsibility toward the global common task of environmental protection.

This study estimates the potential of renewable energy sources for power generation in Bangladesh from the viewpoint of different promising available technologies. Future long-term electricity demand in Bangladesh is projected based on three economic growth scenarios. The energy planning model LEAP is applied to forecast the energy requirements from 2005 to 2035. Different policy scenarios, e.g., accelerated renewable energy production, null coal import, CO_2 emission reduction targets and carbon taxes in the power sector from 2005 to 2035 are explored. The analyses are based on a long-term energy system model of Bangladesh using the MARKAL model. Prospects for the power sector development of the country are identified, which ensure energy security and mitigate environmental impacts.

The technical potential of grid-connected solar photovoltaic and wind energy are estimated at 50174 MW and 4614 MW, respectively. The potential of energy from biomass and small hydro power plants is estimated at 566 MW and 125 MW, respectively. Total electricity consumption was 18 TWh in 2005 and is projected to increase about 7 times to 132 TWh by 2035 in the low GDP growth scenario. In the average and high GDP growth scenarios, the demand in 2035 shows an increase of about 11 and 16 times the base year value, respectively.

The results of the MARKAL analysis show that Bangladesh will not be able to meet the future energy demand without importing energy. However, alternative policies like CO_2 emission reduction by establishing a target, accelerated deployment of renewable energy technologies, or introduction of a carbon tax to promote efficient technologies reduce the burden of imported fuel, improve energy security and reduce environmental impacts. The model predicts that alternative policies will not result in significantly higher cumulative discounted total energy system costs. The system costs increase slightly over the base scenario. The alternative scenarios reduce imported fuel by up to 85 %. The analysis shows a substantially higher implementation of renewable energy technologies compared to the base scenario. Renewable energy technologies, especially solar photovoltaic, play an important role in achieving acceptable energy security.

KURZFASSUNG

Bedeutung erneuerbarer Energien im Elektrizitätssektor von Bangladesch: langfristige Planungsstrategien

Im Hinblick auf seine Energieversorgung steht Bangladesch vor großen Herausforderungen: Sorgen über Energiesicherheit durch wachsende Energieimporte, zu geringe einheimische Ressourcen für die Energieerzeugung sowie ein voraussichtlicher Strombedarf, der die einheimischen Versorgungskapazitäten innerhalb der nächsten Jahre übersteigen wird. Durch das Erschließen des Potenzials für erneuerbare Energiequellen könnte das Land möglicherweise den wachsenden Energiebedarf erfüllen und damit einen besseren Zugang zu Elektrizität für alle erreichen sowie Energiesicherheit durch Entwicklung entsprechender Techniken erhöhen. Die Integration von erneuerbaren Energien in den Elektrizitätssektor durch nationale Energieplanung wäre daher ein Schritt in die richtige Richtung, nicht nur für die nachhaltige Entwicklung des Landes, sondern auch wegen der Verantwortung von Bangladesch hinsichtlich der globalen Gemeinschaftsaufgaben im Bereich Umweltschutz.

Die vorliegende Studie untersucht das Potenzial erneuerbarer Energien aus der Sicht verschiedener vielversprechender und bereits vorhandener Techniken. Der zukünftige langfristige Strombedarf in Bangladesch wird auf der Grundlage von drei Wirtschaftswachstumsszenarien prognostiziert. Mit dem Energieplanungsmodell LEAP wird der Energiebedarf von 2005 bis 2035 vorhergesagt. Verschiedene Politikszenarien, z.B. Erhöhung der Produktion erneuerbarer Energie, keine Kohleimporte, CO_2-Emissionsreduktionsziele sowie eine Kohlenstoffsteuer werden für die Bewertung des Energiesektors von 2005 bis 2035 untersucht. Die Analysen basieren auf einem langfristigen Energiesystemmodell für Bangladesch auf der Grundlage des MARKAL-Modells. Die Studie präsentiert eine Prognose für die zukünftige Entwicklung des Energiesektors des Landes bei gleichzeitiger Sicherung des Energiebedarfs und Reduzierung der Umweltauswirkungen.

Das Potenzial solarer Fotovoltaik und Wind für die Einspeisung in das Stromnetz wird auf 50174 MW bzw. 4614 MW, das von Energie aus Biomasse und kleinen Wasserkraftwerken auf 566 MW bzw. 125 MW geschätzt. Der gesamte Stromverbrauch in 2005 betrug 18 TWh, und er wird in dem Szenario mit niedrigem Wachstum des Bruttoinlandsprodukt (BIP) bis 2035 um das 7-fache auf 132 TWh zunehmen. In den Szenarien mit durchschnittlichem und hohem BIP-Wachstum steigt der Bedarf bis 2035 auf das ca. 11- bzw. 16-fache des Wertes des Grundszenarios.

Die MARKAL-Analyse zeigt, dass Bangladesch die zukünftige Energienachfrage ohne Energieimporte nicht erfüllen kann. Jedoch können durch politische Maßnahmen, wie z. B. die Einführung von CO_2-Emissionsreduktionszielen, die verstärkte Nutzung von erneuerbaren Energien oder die Einführung von Kohlenstoffsteuern zur Förderung effizienter Technologien, die Energieimporte reduziert, die Energiesicherheit verbessert und die Umweltauswirkungen begrenzt werden. Das Modell prognostiziert, dass die politischen Maßnahmen nicht zu signifikant höheren Gesamtenergiesystemkosten führen werden. Die Systemkosten nehmen geringfügig zu verglichen mit denen im Grundszenario. Die alternativeszenarien führen zu einer Reduzierung der Energieimporte um bis zu 85 %. Die Analyse zeigt eine bedeutend höhere Nutzung von erneuerbaren Energien verglichen mit dem Grundszenario. Diese Techniken, insbesondere die Fotovoltaik, spielen eine wichtige Rolle bei der Energiesicherheit Bangladeschs.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

AC	: Alternating current
AIM	: Asian-pacific integrated model
BPDB	: Bangladesh Power Development Board
CC	: Combined cycle
CFL	: Compact fluorescent lamps
DC	: Direct current
DESA	: Dhaka Electric Supply Authority
DESCO	: Dhaka Electric Supply Company Limited
ENPAP	: Energy and power evaluation program
ETA	: Energy technology assessment
FGD	: Flue gas desulphurization
FO	: Furnace oil
GAMS	: General algebraic modeling system
GDP	: Gross domestic product
GHG	: Greenhouse gas
GW	: Gegawatt
HOMER	: Hybrid system optimization model for electric renewables
IAEA	: International Atomic Energy Agency
IEA	: International Energy Agency
IIASA	: International Institute of Applied System Analysis
IPCC	: Intergovernmental Panel on Climate Change
LEAP	: Long-range energy alternative planning
MAED	: Model for analysis of energy demand
MARKAL	: Market allocation
MESSAGE	: Model for energy supply systems analysis and general environmental impact
MSW	: Municipal solid wastes
mton	: million tons
mtoe	: Million ton of oil equivalent
MUSS	: User supports system

MW	: Megawatt
NASA	: National Aeronautics and Space Administration
O&M	: Operation and maintenance
PERSEUS	: Program package for emission reduction strategies in energy use and supply
POLES	: Prospective outlook on long-term energy systems
PSMP	: Power sector master plan
PV	: Photovoltaic
REB	: Rural Electrification Board
RERC	: Renewable Energy Research Center
SCGT	: Simple cycle gas turbine
SC	: Simple cycle
SHS	: Solar home system
SSE	: Surface Meteorology and Solar Energy
ST	: Steam turbine
TDSC	: Total discounted system cost
T&D	: Transmission and distribution
TWh	: Terawatt hour
WASP	: Wien automatic system planning package
Wp	: Watt peak

1 INTRODUCTION

1.1 Problem statement

1.1.1 Energy and environment

The measure of development in any society of today is synonymous with the level of energy consumption. Energy is therefore recognized as a critical input parameter for national economic development. Modern day energy demands are still met largely from fossil fuels such as coal, oil and natural gas. In 1980, the global primary energy demand was only 7228 million tons of oil equivalent (mtoe) but this had increased to 11429 mtoe by 2005 (WEO 2007). Further increases can be expected, mostly in connection with increasing industrialization and demand in less developed countries, aggravated by gross inefficiencies in all countries. Fossil fuels provide energy in a cheap and concentrated form, and as a result they dominate the energy supply. In the worldwide total energy demand, the share of fossil energy is around 80 %, while the remaining 20 % are supplied by nuclear and renewable energy (Rout 2007). In 2005, a total of 26.6 billion tons of CO_2 emissions were generated world-wide of which more than 41 % was from power generation based on fossil fuels (WEO 2007). The CO_2 emissions from power generation are projected to increase 46 % by 2030 (WEO 2007). In 1980, total global electricity generation was 8027 terawatt hour (TWh), which had increased to 17363 TWh by 2005. The installed capacity of power generation was 1945 gigawatt (GW) in 1980 and had increased to 3878 GW by 2005 (EIA 2010) of which almost 69 % was from conventional fuels. The main problem is that in the next 20 years the expected demand for electricity would require the installation of the same power generation capacity that was installed over the entire 20th century. This translates to the stunning number of one 1000 megawatt (MW) power station installed every 3.5 days over the next 20 years (Lior 2008).

The concentration of greenhouse gases (GHGs) in the atmosphere has been increasing for a variety of reasons. CO_2 in the atmosphere is increasing as a result of the burning of fossil fuels. Global warming and mitigation of GHGs are presently the major issues of international concern. The Intergovernmental Panel on Climate Change (IPCC) was set up in 1988 to study different aspects of climate change. One aspect is the progressive gradual rise of the earth's average surface temperature, thought to be caused in part by increased concentrations of GHGs in the atmosphere. This so-called global warming is commonly described as climate change, although it is only one of the changes that affect the global climate. The major key findings of IPCC 4th assessment report are (Dutt and Glioli 2007; IPCC 2007; WEO 2007):

1) Most of the observed increase in globally averaged temperatures since the mid 20th century is very likely due to the observed increase in anthropogenic GHG concentration. Discernable human influences now extend to other aspects of climate, including ocean warming, continental average temperature and temperature extremes.
2) For the next two decades, a warming of about 0.2°C per decade is projected for a range of emission scenarios. Even if the concentrations of all GHGs were to be kept constant at the year 2000 levels, a further warming of about 0.1°C per decade would be expected.
3) Anthropogenic warming and sea level rise would continue for centuries due to the time scales associated with climate processes and feedbacks, even if the levels of GHG concentrations were not to change.

1.1.2 Energy and sustainable development

Sustainable development can be broadly defined as living, producing and consuming in a manner that meets the needs of the present without compromising the ability of future generations to meet their own needs (Twidell and Weir 2006). Energy development is increasingly dominated by major global concerns of air pollution, fresh water pollution, coastal pollution, deforestation, biodiversity loss and global climate deterioration. To prevent disastrous global consequences, it would increasingly be impossible to engage in large-scale energy-related activities without insuring their sustainability, even for developing countries in which there is a perceived priority of energy development and use and electricity generation over their impact on the environment, society, and indeed on the energy resources themselves. The long-term control of global climate change and holding the climate at a safety levels requires a connection of policies for climate change to sustainable development strategies in all nations.

Over the last few decades, a decline in fossil fuels reserves has been observed worldwide. Alternately, fossil fuels are not being newly formed at any significant rate, and thus present stocks are ultimately finite. If the current rate of energy consumption is continued, the limited reserves of coal, oil and natural gas may last only for 122, 42 and 60 years, respectively (BP 2009; Lior 2008). The amount of uranium in the world is insufficient for massive long-term deployment of nuclear power generation (BP 2009; Lior 2008). Therefore, the sustainable development issue is more than ever raised, stimulating the need to search for a sustainable development path. There are two paths to provide energy services to the people (Dabrase and Ramachandra 2000):

1) The hard path or unsustainable path continues with heavy reliance on unsustainable fossil fuels or nuclear power. This leads to serious pollution problems and disposal of radioactive waste problems.
2) The soft or sustainable path relies on energy efficiency and renewable resources to meet the energy requirement.

National energy planning with an emphasis on renewable resources and improvement of energy efficiency contributes to sustainable development. Currently, the centralized planning approach is adopted for resource management and energy policy decisions. There is a need to move towards the softer path to ensure sustainable development for the present and the future. This is the path to increase reliance on clean renewable energy resources and improved energy use efficiency and conversion measures to minimize the loss of primary resources without the risk of climate or ecology breakdown. Consequently, almost all national energy policies include some of the following vital factors for improving or maintaining social benefits from energy (Twidell and Weir 2006):

1) Increased harnessing of renewable supplies
2) Increased efficiency of supply and end-use
3) Reduction in pollution.

1.1.3 Energy situation in Bangladesh

Electricity is a pre-requisite for the technological development and economic growth of a nation. The future economic development of Bangladesh is likely to result in a rapid growth in the demand for energy with accompanying shortages and problems. The country has been facing a severe power crisis for about a decade. Known reserves (e.g., natural gas and coal) of commercial primary energy sources in Bangladesh are limited in comparison to the development needs of the country (Islam 2001a). Power generation in the country is almost entirely dependent on fossil fuels, mainly natural gas, that accounted for 81.4 % of the total installed electricity generation capacity (5248 MW) in 2006 (BPDB 2006). By that year, only about 42 % of the total population had been connected to electricity (Jamaluddin 2008), with vast majority being deprived of a power supply. The government of Bangladesh has declared that it aims to provide electricity for all by the year 2020, although at present there is high unsatisfied demand for energy, which is growing by more than 8 % annually (PSMP 2005). Demand-supply gaps and load shedding have increased (Figure 1.1).

Coal is expected to be the main fuel for electricity generation. The government of Bangladesh has planned to generate 2900 MW power from coal in the next 5 years (Khan 2009), although coal power has adverse environmental effects and coal reserves are limited. The government has also focused on furnace-oil-based peaking power plants. As a result, the share of CO_2 emissions coming from fossil-fuel-based power plants in the national CO_2 inventory is expected to grow, and there is a growing dependency on imported fossil fuels for power generation.

Increasing the use of fossil fuels to meet the growing worldwide electricity demand, especially in developing countries, not only counteracts the need to prevent climate change globally but also has negative environmental effects locally. In Bangladesh, the power sector alone contributes 40 % to the total CO_2 emissions (ADB 1998; Shrestha et al. 2009). In this case, it is necessary to develop and promote alternative energy sources that ensure energy security without increasing environmental impacts.

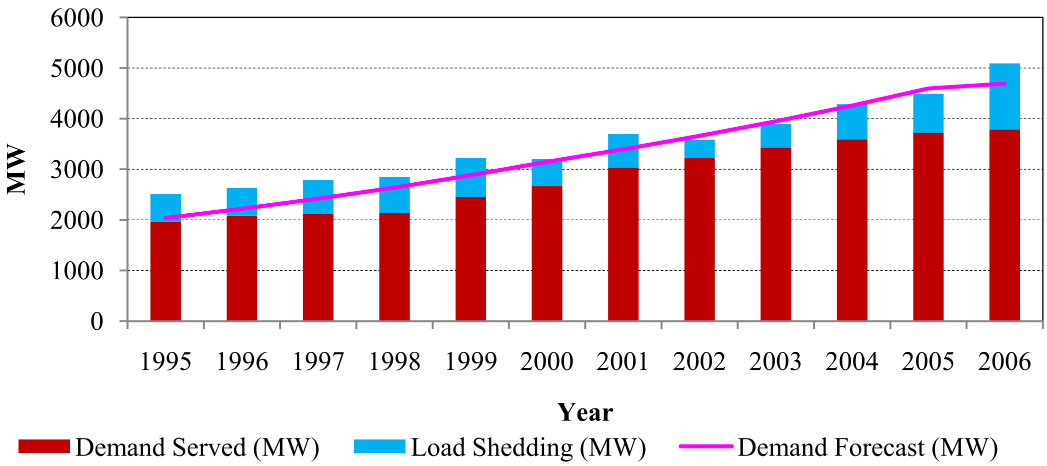

Figure 1.1: Power demand-supply gaps and load shedding in Bangladesh (BPDB 2006)

Bangladesh is facing daunting energy challenges: Security concerns over growing fuel imports, limited domestic energy resources for power generation, and projected demands for electricity that will exceed domestic supply capabilities within a few years.

By acknowledging the potential of renewable energy resources, the country could possibly meet its unprecedented energy demand, thus increasing electricity accessibility to all and enhancing energy security through their advancement. The integration of renewable energy technologies in the power sector through national energy planning would be, therefore, the right direction, not only for sustainable development of the country but also as the responsibility of Bangladesh toward the global common task of environmental protection. In order to avoid long-term impacts, it is necessary to conduct energy planning by generating transient scenarios for demand and the corresponding requirement of energy sources under the constraints of availability, cost and pollution. The present study is one of the first efforts in this direction. It concentrates on the Bangladesh power sector only, as this has become one of the most critical sectors in the country's economy and is a major bottleneck with respect to development.

1.2 Role and prospects of renewable energy

Renewable energy plays an important role in the process of integrating the environment into energy policies through its potential to contribute to the objectives of sustainability.

At the point of power generation, renewable energy sources generally emit no GHGs, with the notable exception of biomass, which is neutral over its complete life-cycle in terms of GHGs. The renewable resources can make an important contribution to the security and diversity of energy supplies by providing a secure, indigenous source of energy that is available in a variety of forms (EEA 2001).

These benefits have created a strong motivation for pursuing renewable energies in both developed and developing countries. For example, the community aim formulated by the European Commission is to cover 21 % of the electricity consumption in 2010 by renewable energy sources (Ringel 2006). The installed capacity of renewable energy technologies (except hydro) was 46 GW in 2000 and had increased to 126 GW by 2007 (EIA 2010). The contribution of renewable energy sources to electricity in Germany was about 37 TWh (6.3 % of gross electricity consumption) in 2000 and had increased to 87 TWh (14.2 % of gross electricity consumption) by 2007 (Busgen and Durrschmidt 2009). Worldwide installed capacities of solar photovoltaic (PV) and wind power grow at 30 % per year compared to the 1.4 % annual growth of conventional energy (BP 2009; EIA 2010; Green 2004). This has led to a significant reduction in the investment cost of solar PV and wind power generation. The unit cost of PV has dropped in several orders of magnitude, and the efficiency is continuously being improved (Brown and Hendry 2009; Gottschalg 2001; Green 2004; Ramana 2005; Van der Zwaan and Rabl 2003). The technology of wind turbines and grid systems are becoming increasingly well developed and their cost has dropped significantly (Neij 1999).

1.3 Energy planning through optimizing energy systems

Energy planning with embedded environmental concerns as demonstrated through this study is therefore needed for optimum utilization of available resources including funds, conservation of fossil fuel reserves and advancement of renewable energy for improving sustainability through reduction of GHG emissions. As energy is a crucial determinant in the development of economy, its availability is almost necessary. Therefore, the following aspects require focused attention:

- Availability of capacity for power generation
- Minimization of generation costs of electricity

- Minimization of consumption of conventional resources
- Demand-supply balancing.

Besides the above issues, this study also focuses on environmental issues that have become increasingly important, especially since the Rio Summit in 1992 and the definition of targets for GHG emission reduction in the Kyoto Protocol of 1998. Therefore, energy planning now includes the following aspects:

- Reduction or control of GHG emissions
- Introduction of carbon taxes
- Promotion of renewable energy systems.

1.4 Research objectives and approach

The main objective of this study is to examine the potential contribution of renewable energy to the future power supply in Bangladesh based on a least cost analysis. The specific objectives are:

1) Assessment of the potential of renewable resources for power generation
2) Projection of the long-term electricity demand
3) Development of a reference energy system for the Bangladesh power sector
4) Analysis of the growth of the Bangladesh power sector based on a cost-benefit analysis including an assessment of the introduction of emission reduction targets and carbon taxes through development of future scenarios
5) Assessment of resource use and GHG emissions for all generated scenarios.

The following methodological approaches are developed in connection with the above-mentioned objectives:

1) Assessment of the potential of renewable energy resources for power generation
2) Projection of the long-term electricity demand
3) Development of the MARKAL (market allocation)-Bangladesh model as an analytical planning tool for the Bangladesh power sector
4) Development of future scenarios for the Bangladesh power sector covering changes in resource constraints, cost factors, and technological development.

In this study, a MARKAL energy-system model for the Bangladesh power sector is developed to analyze alternative technological options for the next 30 years considering the base year 2005 for addressing the above-mentioned challenges. The intention is not to predict the future, but to provide insights into the implications of energy technology options that can be pursued by Bangladesh. Future possibilities are covered by different scenarios. Possibilities for the expansion of the power sector and the effects of introducing new policies like CO_2 emission reduction targets or carbon taxes in Bangladesh are assessed. The study also projects the electricity demand for the next 30 years using the Long-range Energy Alternative Planning (LEAP) model and assesses the renewable energy potential for power generation in Bangladesh.

1.5 Structure of the thesis

In Chapter 2, a review of existing tools related to energy planning is given together with a description of the MARKAL model selected for this study. Chapter 3 focuses on the assessment of the technical potential of various renewable resources for power generation along with suitable technologies. Chapter 4 is devoted to the forecast of the electricity demand. The LEAP model along with three scenarios, namely low gross domestic product (GDP) growth, average GDP growth and high GDP growth, employed to project the demand is discussed in this chapter. Chapter 5 deals with the development of the MARKAL-Bangladesh model. It covers the development of a reference energy system for the Bangladesh power sector. This chapter includes background information related to availability of resources, conversion technologies characteristics, growth constraints and other major parameters that are supplied as input to the MARKAL model. This chapter also presents the study boundaries and assumptions. Chapter 6 presents the future scenarios and the results for all scenarios. Chapter 7 provides the conclusions of the study.

2 TOOLS AND METHODS

2.1 Review of energy planning models

Energy planning is an important task for both national governments and international agencies, as it supports decision making with respect to national and international development. The energy planning discipline dates from the 1960s (Nguyen 2005), where the first studies focusing on energy supply were carried out. At that time, planning methodologies focused on different aspects such as cost, environmental damage or energy supply security. After the oil crisis in the early 1970s, energy planning became very important, especially for policy makers. Only after the oil crisis was sufficient attention given to critical assessment of fuel resources, rational use and conservation of energy resources, and long-term energy planning (Mathur 2001). In addition to this, the Rio Earth Summit in 1992 triggered environmental studies on the issue of GHG emissions. This was especially the case after the report of the IPCC in 1995, which concluded that CO_2 emission has a noticeable impact on the environment. Intensive discussions and debates followed, legislation was formulated and GHG emission reduction targets set (e.g. Kyoto Protocol, 1998). Aggregated energy-related activities contribute 80 % to the total greenhouse effect worldwide (IPCC 1995). This has created a need for new energy planning models that consider environmental problems. Therefore, besides separate models for environmental studies pertaining to assessment, projection and mitigation, energy planning models were expanded to cover the environmental aspects of power generation.

Energy planning models differ from each other in the model purpose, model structure (e.g., internal and external assumptions), analytical approach (e.g., top-down or bottom-up), study methodology, mathematical approach, geographic coverage, sectoral coverage, time horizon, and data requirement (Figure 2.1). Energy-economy models are used for energy and environmental policy analysis (Table 2.1). The most important models and practices that have evolved in the field of energy-environmental planning are macroeconomic models, energy demand and supply models, modular package models and integrated models.

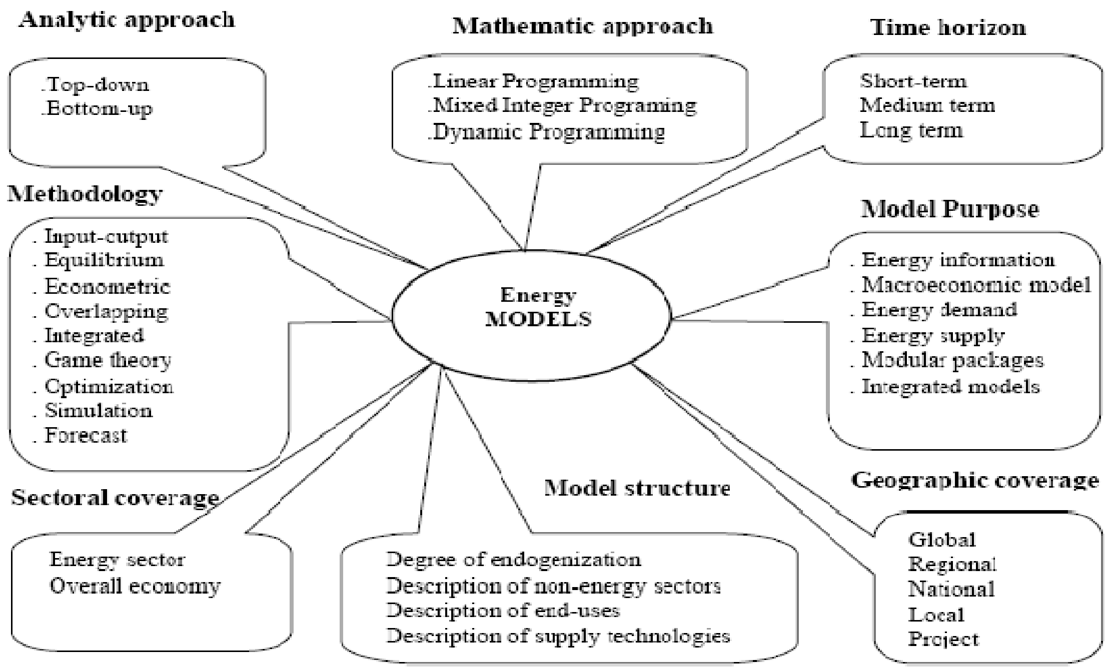

Figure 2.1: Criteria for classification of energy planning models (Nguyen 2005)

Table 2.1: Classification of energy-economy models (Pandey 2002)

Paradigm	Space	Sector	Time	Examples	Issues addressed
Top-down simulation	Global, national	Macro-economic/ energy	Long-term	Integrated assessment (e.g., AIM) and general equilibrium models), input-output models, and system dynamics models (e.g. FOSSIL2)	Impact of market measures and trade policies on cost to economies and global/national emissions
Bottom-up optimization /accounting	National, regional	Energy	Long-term	Optimization (e.g., MARKAL, EFOM) and accounting (e.g., LEAP) models	Impact of market measures and other policies (e.g., regulations) on technology-mix, fuel-mix, emissions, and cost to energy system; capacity investment planning
Bottom-up optimization /accounting	National, regional, local	Energy	Medium-term/ short-term	End-use sectors models (e.g., AIM/End use), power sector, coal sector models	Impact of sectoral policies on sectoral technology-mix, fuel-mix, coats and emissions; planning for generation-mix; unit scheduling; logistics

2.1.1 Macroeconomic models

Macroeconomic models are concerned with questions on how the price and availability of energy influence the economy in terms of GDP, employment or labor and inflation rate and vice versa. These models have an aggregate macroeconomic module linked to a bottom-up energy supply module. Three examples under this category are MACRO, ETA-MACRO and MARKAL-MACRO.

MACRO: The MACRO model was developed by the International Institute of Applied System Analysis (IIASA). The model is a two-sector (production and consumption), aggregated view of long-term economic growth. The model has eleven regional versions and is widely used to compute size of economy, investment flows, demand of energy and non-energy products and inter-industry payments. The model's strength is that it treats the economy of coherent regions of the world in an integrated fashion and estimates energy demand. Its weakness is that the model has little resolution of technological choices (Grubler et al. 1999).

ETA-MACRO: The ETA-MACRO model is a general equilibrium model comprising an energy technology assessment (ETA) model coupled with a macroeconomic growth model (MACRO). The model uses non-linear optimization. Energy demands and costs receive a feedback and are modified on the basis of the information from the economic model. This connection allows the energy model to interact with the macro-economy of the region/country under consideration.

MARKAL-MACRO: The MARKAL-MACRO model is similar to the ETA-MACRO model except that the ETA model is replaced by the much more detailed MARKAL model. In both models, the macro-economy is represented by a single production function with energy, employment or labor, and capital as the inputs, which does not consider the traditional sector. The integration of MARKAL is a good example of combined bottom-up and top-down modeling techniques.

2.1.2 Energy supply models

Energy supply models are often concerned with determining the least-cost options of an energy supply system meeting a given demand and subject to a number of constraints. These models generally use an optimization or a simulation method, where the optimization is usually based on linear and non-linear programming. Some of the energy supply models are extended to include parts of the energy demand analysis, and others provide additional features to calculate the impacts on the planned energy system including emissions, economic and social aspects. Representative energy supply models are: MARKAL, MESSAGE, POLES and WASP.

MARKAL: The unique feature of the MARKAL model is that it solves the energy system as a multi-period linear program; hence it is called a linear programming tool. The solution satisfies an exogenously specified set of energy service demands, minimizing the total system discounted costs. A number of technologies compete to satisfy a specific demand and supply of energy. MARKAL has been adopted in energy and environmental studies in over 70 countries and is one of the most widely used energy models in the world. This model is applied in this study (section 2.2).

MESSAGE: The Model for Energy Supply Systems Analysis and their General Environmental Impact (MESSAGE) was developed by IIASA and is a dynamic linear programming model, calculating cost-minimal supply structures under the constraints of resource availability, given technologies, and particular energy demand. It models flows of energy through the energy system, from primary energy extraction via conversion up to final utilization in various sectors of the economy. MESSAGE uses two major types of variables: an activity variable (describing the fuel consumption of technology) and a capacity variable (annual new installations of technologies). The constraints applied in all modeling exercises are acquiring sufficient supplies of the exogenous demand, balancing quantities for all energy carriers and periods, constraining resource availability, and ensuring the installation of sufficient capacity of the technology applied. The objective function generally applied in MESSAGE is to minimize the sum of the discounted costs (Messner 1997).

POLES: The Prospective Outlook on Long-term Energy Systems (POLES) model is a simulation model providing long-term energy supply and demand scenarios on the basis of hierarchical systems of interconnected sub-models at international, regional and national levels. The impact of the emissions reduction strategies on the international energy markets can be assessed. A detailed description of the oil, gas and coal market at a world level allows a significant increase in the size and complexity of the model (Nguyen 2005).

WASP: The Wien Automatic System Planning Package (WASP) model permits the user to find an optimal expansion plan for a power generating system over a long-term period within the constraints defined by the modeler. The model is maintained by the International Atomic Energy Agency (IAEA), which has developed four versions of the program. In WASP, the optimum expansion plan is defined in terms of minimum discounted costs. Using the electricity demand for the future years, the model explores all possible sequences of capacity additions that could be added to the system within the required constraints (Connolly et al. 2010).

2.1.3 Energy demand models

Energy demand models are built to forecast the energy demand of either the entire economy or of a certain sector. Among the energy demand models, the techno-economic models are widespread, but econometric models are also used. Representative energy demand models are MEDEE, and MAED.

MEDEE: Modele d' Evaluation de la Demande En Energie (MEDEE) was developed by the Institute of Energy Policy and Economics, Grenoble, France. MEDEE is a techno-economic bottom-up model for long-term energy demand forecast. It follows the end-use method. By breaking up the energy demands into homogenous subgroups and identifying the direct and indirect determinants of these demands, the model is able to evaluate the future energy demand based on the evaluation of these determinants (Nguyen 2005).

MAED: The Model for Analysis of Energy Demand (MAED) is a simulation model designed to evaluate medium-term and long-term demand for energy in a country or region. The model was developed by the IAEA and was originally based on work done at the University of Grenoble in France. The model offers an alternative approach to MACRO/DEMAND/BALANCE for estimating energy demand and electricity demand. The model consists of three modules: an energy demand module that calculates the final energy demand, an hourly electric power demand module converts the total annual demand for electricity in each sector, and a load duration curve module ranks the hourly demands imposed on the grid. The output of the model consists of detailed estimates of alternative energy forms used in each sub-sector for each selected year (Rostamihozori 2001).

2.1.4 Modular packages

These packages consist of different kinds of models such as a macroeconomic component, an energy supply and demand balance, an energy demand alone, etc., which are integrated into a package. The modeler does not need to run all the models but may select only a subset depending upon the nature of the analysis to be carried out. Some of the well-known packages are LEAP, ENPEP and MESAP.

LEAP: The Long-range Energy Alternative Planning (LEAP) is an integrated modeling tool that can be used to track energy consumption, energy production, and resource extraction in all sectors of an economy. The model was developed in 1980 in the USA and is currently maintained by the Stockholm Environment Institute (SEI). LEAP is usually used to analyze national energy systems. It functions using an annual time step, and the time horizon can extend for an unlimited number of years (typically between 20 and 50). The model supports a number of different modeling methodologies. On the demand side these range from bottom-up, end-use accounting techniques to top-down macroeconomic modeling. On the supply side LEAP provides a range of accounting and simulation methodologies for modeling electricity generation and capacity expansion planning (Connolly et al. 2010). The demand module is used in this study to forecast electricity demand (Chapter 4).

ENPEP: The Energy and Power Evaluation Program (ENPEP), developed by the Argonne National Laboratory in the USA, is a simulation type model used to model a country's entire energy system. The model incorporates the dynamics of market processes related to energy by an explicit representation of market equilibrium, i.e., the balancing of supply and demand. It consists of an executive module and ten technical modules. The main module is BALANCE. This module uses a non-linear and market-based equilibrium approach to determine energy supply and demand balance for the entire energy system (Khalaquzzaman and Kim 2008). Equilibrium is reached when ENPEP-BALANCE finds a set of market clearing prices and quantities that satisfy all relevant equations and inequalities (Connolly et al. 2010).

MESAP: The Modular Energy System Analysis and Planning (MESAP) software is a tool for integrated energy and environmental planning. The tool was developed at the Institute of Energy Economics and Rational Use of Energy (IER), University of Stuttgart, in 1997. It offers models for investment calculation, energy and environmental accounting, energy demand analysis, integrated resource planning, demand-side management, electricity operation and expansion planning as well as life cycle and fuel chain analysis. The MESAP consists of three layers of modules: the database tools, the models, and the external information systems. Backbone of the database is the database management system. The planning tools include: PlaNet for demand and supply simulation, INCA for investment calculation and financial analysis, and TIMES for energy system optimization (Nguyen 2005).

2.1.5 Integrated models

Integrated models consist of an integrated set of equations that are simultaneously solved. These tools usually cover energy-economy-environmental interactions. Some of the well-known models are AIM, IMAGE 2.0 and PERSEUS.

AIM: The Asian-Pacific Integrated Model (AIM) is a large-scale model for scenario analyses of GHG emissions and the impacts of global warming in the Asian-Pacific region. The model was developed mainly to examine global warming response measures in the Asian-Pacific region, but it is linked to a world model to also make global estimatesl. The model comprises three main modules: the GHG emission model (AIM/emission), the global climate change model (AIM/climate), and the climate change impact model (AIM/impact). Bottom-up models can reproduce detailed processes of energy consumption, industrial productions, land-use changes and waste management as well as technology development and social energy demand changes. On the other hand, top-down models can estimate interactions between the energy and economic sector, and between land-use changes and the economic sector. The original AIM bottom-up components are integrated with two top-down models through a linkage module. This new structure maximizes the ability to simulate a variety of inputs at a variety of levels and to calculate future GHG emissions in a relatively full range analysis (Mathur 2001).

IMAGE 2.0: The IMAGE 2.0 model is a multi-disciplinary, integrated model designed to simulate the dynamics of the global society-biosphere-climate system. It consists of three fully linked sub-systems: energy-industry, terrestrial-environment, and atmosphere-ocean. The energy-industry sub-model computes the emissions of GHG in thirteen world regions as a function of energy consumption and industrial production. The terrestrial-environment sub-model simulates the changes in global land cover on a grid scale based on climate factors and economic factors. The atmosphere-ocean sub-model computes the build-up of GHG emissions in the atmosphere and the resulting zonal average temperature and precipitation patterns (Mathur 2001; Nguyen 2005).

PERSEUS: The Program package for Emission Reduction Strategies in Energy Use and Supply (PERSEUS) was developed at the University of Karlsruhe for optimizing energy and material flow as a tool for strategic planning of energy utilities. The model is based on a multi-periodic, mixed integer linear optimization approach. The present and future power plant technologies are characterized in great detail by technical, economical and environmental parameters. To account for the growing uncertainty of input data in liberalized markets, stochastic programming techniques have been integrated. The complex network of supply-side and demand-side options and their interdependencies are represented, and the model minimizes the costs for achieving a given reduction target with the help of linear programming revealing the necessary actions. In contrast to the widely used target function of cost minimization, a profit maximization approach that better reflects the situation in liberalized markets has also been implemented. This approach allows consideration of purchase and sale on spot markets and exchange for electricity (Mathur 2001).

2.2 The MARKAL model

MARKet ALlocation (MARKAL) is an energy planning tool that was developed in 1974 just after the oil crisis by a consortium of members of the International Energy Agency (IEA) based on the General Algebraic Modeling System (GAMS) – a computer language specifically designed to facilitate the development of algebraic models. The Brookhaven National Laboratory (BNL), New York, USA, and the Kernforschungsanlage Jülich (KFA), Jülich, Germany, are the hosts of the program. The MARKAL acronym indicates the intention of its developers to build an instrument for the analysis of the market potential of energy technology and fuels. MARKAL is a large-scale model used for long-term analysis of energy systems for a city, province, country or region. It is a linear programming model that identifies the technological configuration of an energy system, subject to user-specified constraints, that minimizes the total discounted energy-system costs (Fishbone 1983).

Later, many modifications were made to MARKAL, resulting in the present variants of the model. The introduction of the MARKAL User Supports System (MUSS), MARKAL-MACRO and the Windows-based ANSWER were the major events. The MUSS is a user-friendly environment permitting very quick and easy development and maintenance of the database as well as management of the different scenarios under study. The MUSS manages all the input data required by MARKAL, organizes datasets into scenarios to foster sensitivity analysis, integrates seamlessly with the modeling system, and manages the results from model runs. The Windows interface, called ANSWER, was introduced in 1998. With this Windows-based system, the model is more readily accessible and usable to the energy policy and energy system analyst. ANSWER provides a number of enhancements over MUSS for the analysis and presentation of input assumptions and results.

The driving force of the MARKAL model is social and economic development (Figure 2.2; Chen et al. 2006; Zongwin et al. 2001). The environment is an important constraint on development. The energy demand is driven by the availability of technology and the primary energy resources that can be exploited. These factors will then determine the energy consumption in the various economic sectors, the capital needs and technology deployment, and the effects on the environment through pollutant releases to various ecological systems.

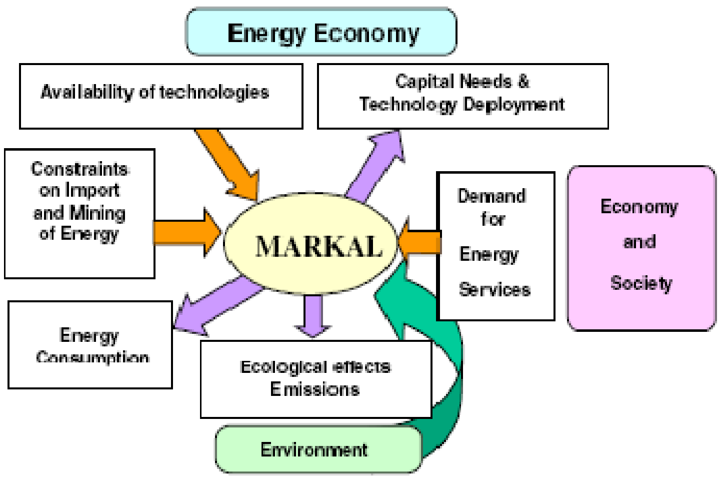

Figure 2.2: Schematic structure of the MARKAL model (Chen et al. 2006; Zonooz et al. 2009)

The MARKAL model mainly consists of the description of a large set of energy technologies, linked together by energy flows, jointly forming a reference energy system. The reference energy system is the structural backbone of MARKAL for any particular energy system, and its great advantage is that it gives a graphic idea of the nature of the system. Another important characteristic of MARKAL is that it is driven by a set of demands for energy services. The feasible solutions are obtained only if all specified end-use demands for energy for all the periods are satisfied. The user exogenously supplies these demands in the model. Once the reference energy system has been specified, the model generates a set of equations that hold the system together. In addition, the MARKAL model possesses a clearly defined objective, which is usually chosen to be the long-term discounted costs of the energy system. The objective is optimized by running the model, which means that configuration of the reference energy system is dynamically adjusted by MARKAL in such a way that all MARKAL equations are satisfied, and the long-term discounted system costs are minimized. In this process, the model computes a partial equilibrium of the energy system for each period, i.e., a set of quantities and prices of all energy forms, such that supply equals demand in each period. A variety of constraints can be supplied to MARKAL for making the solution more realistic. The basic constraints of the model take into account the following (Lanloy and Fragniere 2000):

1) The satisfaction of useful demands
2) The limits on emissions of various pollutants imposed on the system for environmental reasons
3) The energy balance for each energy carrier at different levels of the energy system
4) The capacity transfer between successive periods and the capacity expansion due to investment
5) The bound on production due to installed capacities or limited fuel supply
6) Various other technological constraints needed to represent the complex production systems involved.

2.2.1 Reference energy system

The reference energy system is a way of representing the activities and relationships of an energy system depicting energy demands, energy conversion technologies, fuel mixes, and the resources required to satisfy the energy demands. The reference energy system concept is central to MARKAL, and the most convenient way of expressing the reference energy system is through its graphic format, which is a networked diagram indicating energy flows and the associated parameters of technologies employed in the various stages of the energy system.

The reference energy system can be extended to show emissions when energy is transported or converted from one form to another. The model describes the routes, energy conversion and distribution technologies and also emissions control options. MARKAL indentifies those routes and technologies that best satisfy the overall objectives of the energy system. The model describes the technical and economic properties of each technology and may also describe the technical and behavioral constraints upon their implementation (Manne and Wene 1992).

2.2.2 MARKAL methodology

The standard MARKAL version was used in this study. It requires the user to initially generate a set of projected energy service demands and to input them to the model for every interval in the analysis period. The user must also input the costs for primary energy production, specify primary energy resource supply limits, and create profiles for all current and new energy supply technology options available to the model (capital costs, operation and maintenance costs, efficiencies, pollutant emissions, growth constraints, etc.). MARKAL determines the combination of energy resources and conversion technologies that minimizes the overall energy-system costs for meeting the specified energy demands throughout the economy over the analysis period. The user may specify environmental and other constraints under which the model must satisfy the energy supply-demand balance. The design of the model enables a wide variety of "what if" analyses to be carried out, e.g., alternative sets of policy, technology or environmental constraints. Values for all user-specified inputs must be provided at each 5-year time step during the analysis period, which is 2005 - 2035 in this study.

The model consists of a set of constraints (equations and in-equations), and one objective function (the total discounted energy system cost). The constraints and objective function are mathematically expressed in terms of two types of quantities, which are decision variables and the parameters. The decision variables are unknown quantities which MARKAL has to determine, whereas the parameters are known quantities that are specified by the user. The variables and parameters are selected in order to be able to state precisely all important constraints of the energy system. There are six sets of variables in the MARKAL model as given below:

1) *INV (k, t)*: the investment in technology k, at period t;
2) *CAP (k, t)*: the capacity of technology k, at period t;
3) *ACT (k, t)*: the activity of technology k, at period t;
4) *IMP (i, t)*: the amount of energy import, of form i, at period t;
5) *EXP (i, t)*: the amount of energy export, of form i, at period t;
6) *ENV (t, p)*: the emission of pollutant p, at period t.

The MARKAL constraints are summarized below in the simplified form from the detailed mathematical formulation given in the MARKAL user manual. In the notations used below, the names of variables appear in upper-case italics and the parameters in lower-case italics.

Flow conservation

For the flow of each energy form, the consumption must not exceed the availability through the inequality according to:

$$\sum_k out_{k,f} \cdot ACT(k,t) + \sum_s IMP(f,t) - \sum_k inp_{k,f} \cdot ACT(k,t) - \sum_d EXP(f,t) \geq 0 \qquad (2.1)$$

where k = energy technology in the model, f = any form of energy, $out_{k,f}$ = amount of energy form f produced by one unit activity in technology k, and $inp_{k,f}$ = amount of energy form f consumed by one unit of activity of technology k.

Demand satisfaction

The demand for each energy service *d* must be met at each period through the following condition:

$$\sum_{k} CAP(k,t) \geq dem_{d,t} \tag{2.2}$$

where $dem_{d,t}$ = demand for end-use of energy (electricity) at period *t* and the simulation is done over all the technologies *k*, which produce energy for demand d. The demand in the above expression is the gross demand that includes losses in the transmission, distribution and utilization, incorporated through different parameters in the model.

Capacity transfer

In case of each technology *k*, total capacity at any period results from the capacity installed previously that is still operative, the initial capacity and the investment in new capacity:

$$CAP(k,t) - \sum_{p} INV(k,p) \leq resid_{k,t} \tag{2.3}$$

where $resid_{k,t}$ = residual capacity of technology *k* at period *t*; the summation extends over all previous periods *p* such that *t-p* does not exceed the life time of the technology *k*.

Capacity utilization

In each technology *k*, activity must not exceed the installed capacity at any time period *t*:

$$ACT(k,t) - util_{k} \cdot CAP(k,t) \leq 0 \tag{2.4}$$

where $util_{k}$ = the annual utilization factor of technology *k*. The electricity generation technologies may have a single annual utilization factor or seasonal utilization factors the sum of which should be less that unity.

Source capacity

Use of any energy carrier or form of energy f through technology *k* must not exceed the annual availability of its capacity at any time period *t*:

$$\sum_{k} inp_{k,f} \cdot ACT(k,t) \leq \sum_{i} srcap_{f,t,i} \tag{2.5}$$

where $srcap_{f,t,i} =$ the annual availability of energy form *f* from source *i* at period *t*.

Growth constraint

Due to reasons like limited extraction facilities for fuel or sometimes regional priorities and constraints, the capacity of each technology cannot grow by more than a certain percentage in each period:

$$CAP(k,t+1) - (1 + growth_{k}) \cdot CAP(k,t) \leq 0 \tag{2.6}$$

where $growth_{k}$ = maximum allowable growth factor for each technology at period *t*.

Emission constraints

Emission constraints specify the upper limit on emissions of certain pollutants by the energy system as a whole. These limits can be imposed in two ways, separately for each time period or cumulative over the whole planning horizon. For these constraints to be active within the model, emission coefficients must have been defined for all polluting technologies. Instead of an emission limit, the user may also specify an emission tax $Etax(t,p)$. If so, the quantity $ENV(t,p).Etax(t,p)$ is added to the annual cost expression, penalizing emissions at a constant rate. The total emissions and emissions limit can be expressed as:

$$ENV(t,p) = \sum_k \left[EMINV(t,p,k) \cdot INV(t,k) + EMCAP(t,p) \cdot CAP(t,k) + EMACT(t,p,k) \cdot \sum_s ACT(t,k,s) \right] \tag{2.7}$$

and

$$ENV(t,p) \le ENV\_LIMT(t,p) \tag{2.8}$$

where $EMINV, EMCAP, EMACT$ = emission coefficients for pollutant p linked respectively to the construction, capacity and activity of a technology. $ENV\_LIMT(t,p)$ = upper limit set by the user on the total emission of pollutant p at time period t.

Other constraints

Other constraints may be built explicitly by the modeler. These constraints are en-equalities showing that the market share of a certain technology or group of technologies cannot exceed a certain fraction. All these special constraints are easily programmed in MARKAL by means of special data tables (ADRATIO tables).

Objective function

The objective function is optimized by the MARKAL model. Usually it is the total discounted system cost (TDSC), which is the combination of five types of cash costs:

$$TDSC = Technology\ \cos t + Import\ \cos t - Export\ revenue - Salvage\ value + Emission\ \ fees \tag{2.9}$$

where

Technology cost is the discounted sum of all technological investments and operation and maintenance (O&M) costs. It is expressed in terms of the three types of technology variables *INV*, *CAP* and *ACT*.

Import cost is the discounted cost of imports of energy. It involves the *IMP* variables. *Export revenue* is the discounted sum of exports revenue earned from export of energy the reference energy system. It involves the *EXP* variables.

Salvage value is the residual monetary value of all the investments remaining at the end of the planning horizon, and discounted to the beginning of the first period like other costs. It is an important refinement, which avoids largely the distortions that would otherwise plague the model's decision towards the end of the planning horizon. Without this corrective term, the model would tend to avoid new investments toward the later analysis periods, since such investment would be productive over a short duration only.

Emission fees (emission taxes) are paid if the model user specifies a cost per ton of emissions within the *ENV* table of parameters. The parameters may involve any MARKAL variable (technology variables, imports, exports, etc.) that has an effect on the total amount of emissions like capacity level, activity level and others. The specification of emission fees or taxes is an alternative to the use of emission constraints.

The set of variables and constraints constituting the model of the energy system is defined in the form of a coefficient matrix (Figure 2.3).

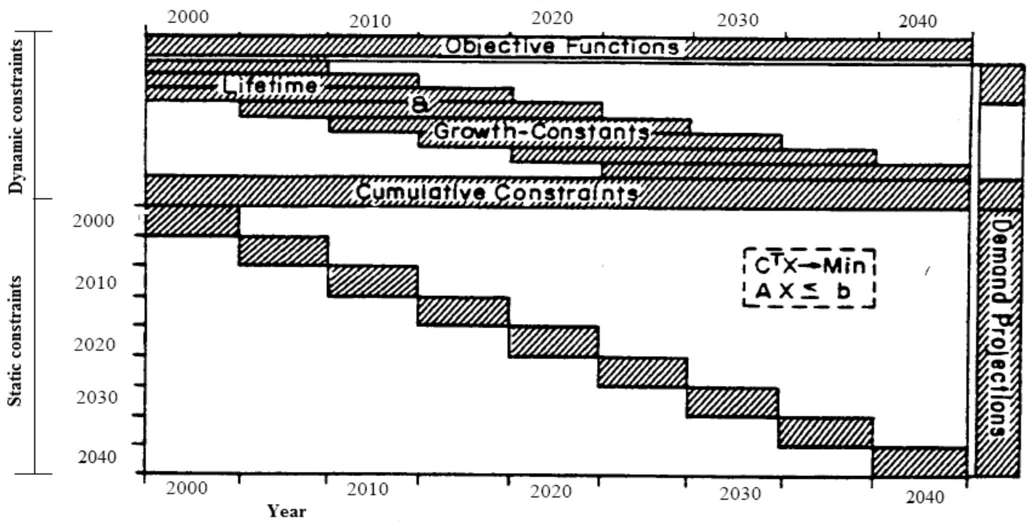

Figure 2.3: Structure of the multi-period MARKAL matrix (modified from Mathur 2001)

The multi-period MARKAL matrix consists of the main matrix while each box represents a sub-matrix with non-zero coefficients. The X-axis of the matrix is the time horizon of the study with segments representing the length of each time period. The Y-axis is divided into two sections, i.e., a lower section representing static or time-independent constraints and an upper section with dynamic constraints or time-dependent constraints. The horizontal bars in the area of the dynamic constraints represent dynamic constraints relevant in different time periods and may cross boundaries of single time periods, start from any point of time, and end at any time within the time span of the study. The bars in the lower section represent cumulative constraints such as an upper limit on cumulative coal and gas consumption; they are relevant over the entire period and are to be satisfied in each period. They also represent static constraints that are confined to a certain time period in the study only as a bound on the capacity in a certain period. The bound may have a different value for each time period, and each value is relevant for the specific time period only. Therefore, the length of these boxes does not exceed the length of the single time period. The complexity of the matrix depends upon types of energy carriers, conversion technologies, emissions and their linkage in the RES (Mathur 2001).

2.2.3 MARKAL input

Input specifications such as technology performance data, emission data, economic data, etc., are required by MARKAL (Figure 2.4). The model builds a representation of the energy system for a given region by specifying energy flows in and out of each technological component in the system.

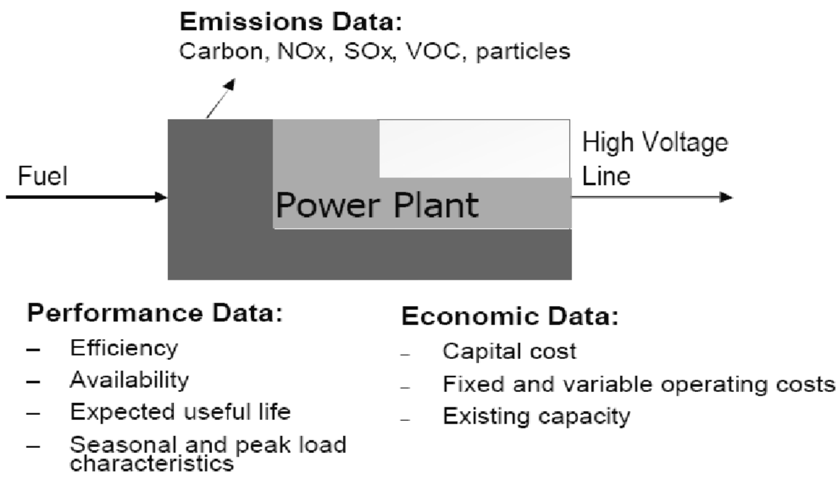

Figure 2.4: MARKAL component block example (Zongwin et al. 2001)

MARKAL requires extensive data input, which can be classified as follows:

1) The global component comprises data parameters that describe some aspect of the global energy system such as the discount rate.
2) The energy carrier component encompasses all energy forms in the energy system.
3) The end-use demand component comprises demands for end-use energy services in the economy.

4) The demand technology component refers to the technologies that consume energy carriers to meet end-use demands.
5) The conversion technology component refers to all power plants that generate electricity.
6) The process technology component indicates all processes that convert one energy carrier to another.
7) The resource technology component refers to the means by which energy enters into the energy system.
8) The constraint component comprises user-defined constraints that are additional to the standard constraints of the MARKAL model.
9) The emission component encompasses environmental impacts of the energy system.

Each group of input data requires a set of defined information (Table 2.2), and the user has to choose proper units for costs, energy flows, final energy demands, activity levels, and capacities of conversion technologies (Noble 2007).

Table 2.2: Standard data needed for MARKAL

Group	Basic information needed for MARKAL
Technologies	Investment cost, fixed and variable operating costs, technical characteristics such as conversion efficiency, capacity, availability factor and productive life of technologies
Energy carriers	Resource costs such as import and extraction costs, annual or cumulative limits on availability, period of resource availability
End-use demand	Specified in terms of energy requirement or useful energy demand
Other constraints	Additional constraints using ADRATIO table
Emissions	Emission factors according to source of a fuel (e.g., CO_2 emission from coal import)

2.2.4 MARKAL output

A typical MARKAL solution consists of the following results (Mathur 2001; Nguyen 2005; Noble 2007):

1) A set of investments in all technologies selected by the MARKAL at each time period. This set refers to the level of new investments expressed in terms of plant capacity of each technology in each period.

2) A set of operating levels of all technologies at each period; the model suggests the optimum utilization level of each technology. It is expressed in terms of percentage utilization of installed power generation capacity.

3) The quantities of each fuel produced, imported, and/or exported at each period. Based on the information on plant capacity and utilization factors, the model gives the total quantity of each fuel required or consumed in the energy system in each period.

4) The emission of pollutants at each period. If sufficient information about different emissions is provided in terms of coefficients for each technology, this emission result set provides values of total emissions due to the utilization of different technologies.

5) The overall system total discounted cost. It is the minimum value of operation of the reference energy system under the defined energy demand levels for each time period of the study. It is the value of the objective function of the MARKAL.

2.3 Similar studies with MARKAL

Energy planning studies are being conducted worldwide in many countries using various tools and practices. MARKAL alone is being used in more than 70 countries and 230 institutes for this purpose (Goldstein and Tosato 2008). It is not possible to cover all studies conducted by MARKAL so far, however, a list of a few of such studies conducted in some developing countries is given (Table 2.4). Bangladesh conducted a study on Asia Least-cost Greenhouse Gas Abatement Strategy (ALGAS) in 1998 using MARKAL that was executed by the Asian Development Bank to project GHG emissions to 2020 and to analyze GHG abatement options in energy, forestry and land use, and agriculture sectors (ADB 1998).

Table 2.4: Selected studies on renewable energy conducted using MARKAL

Study	Reference
Renewable energy technologies for the Indian power sector: mitigation potential and operational strategies	Ghosh et al. 2002
Investigation of greenhouse gas reduction potential and change in technological selection in Indian power sector	Mathur et al. 2003
Long term optimization of energy supply and demand in Vietnam with special reference to the potential of renewable energy	Nguyen 2005
Future implications of China's energy-technology choices	Larson et al. 2003; Zongwin et al. 2001
Modeling China's energy future	DeLaquil et al. 2003
A power sector analysis for Cuba using MARKAL/TIMES model	Wright et al. 2009
Costing a 2020 target of 15% renewable electricity for South Africa	Marquard et al. 2009
Renewable energy resources and technologies in Nigeria: present situation, future prospects and policy framework	Akinbami 2001
Renewable energy utilization in Latvia	Shipkovs et al. 1999

2.4 Adopted methodology

In this study, several methodologies were applied to assess the potential of renewable energy; the LEAP methodology was applied for energy demand projection (Figure 2.5). The MARKAL model with the ANSWER interface was selected and adapted to the Bangladesh power sector. The generation sector in the MARKAL-Bangladesh database characterizes existing and new technologies available for electricity generation. Based on sector-specific electricity demand (residential, commercial, industrial, agricultural and other), fuel prices, technology costs, and the environmental and operational constraints incorporated in the model, MARKAL determines the least cost way of meeting the system electricity demand.

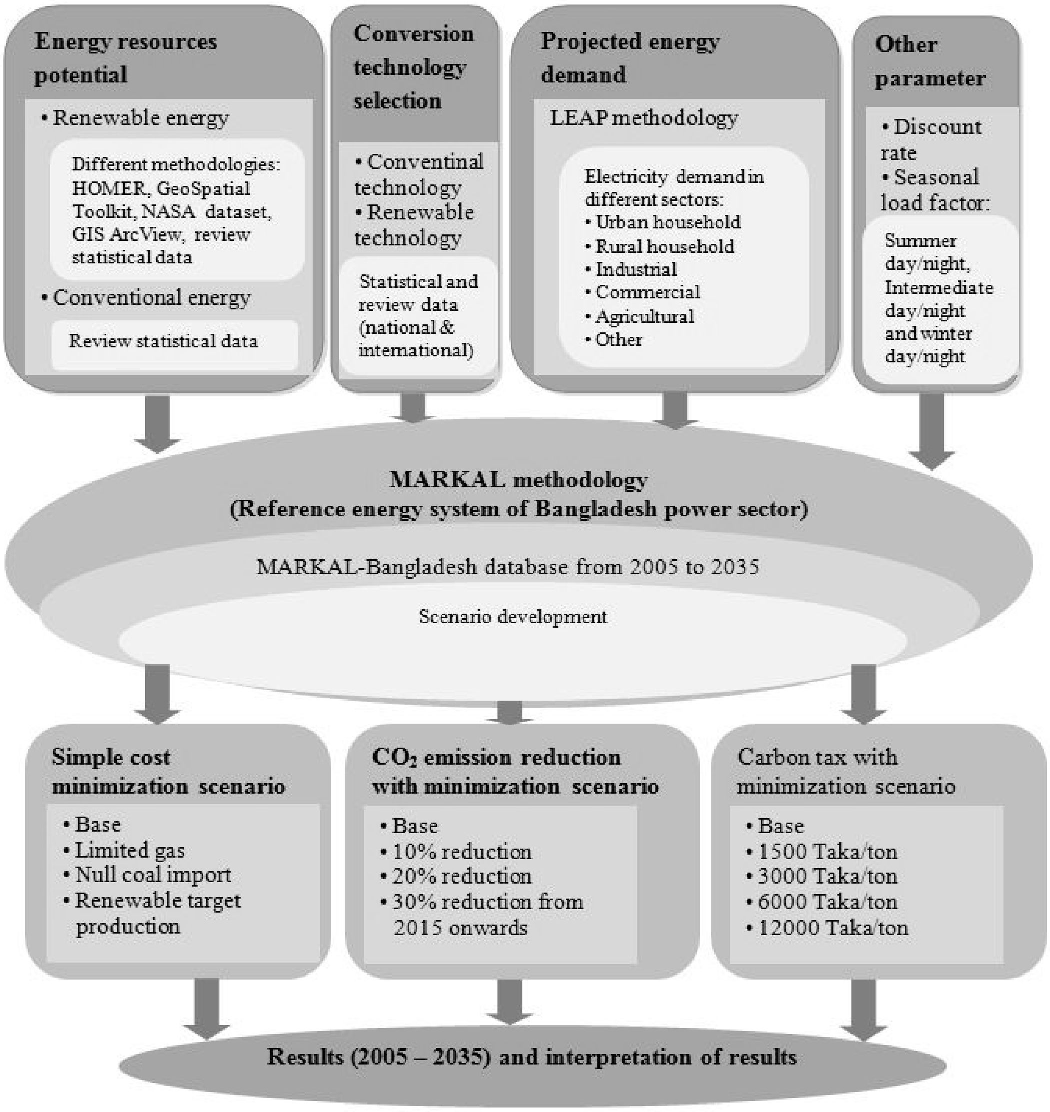

Figure 2.5: Methodology adopted in the study

3 ASSESSMENT OF RENEWABLE ENERGY RESOURCES

Renewable energy encompasses a broad range of energy resources. Bangladesh is known to have a good potential for renewable energy, but so far no systematic study has been done to quantify this potential for power generation. In this chapter, the potential of renewable energy for electrical power generation in Bangladesh is estimated from the viewpoint of different promising available technologies. It also describes the future prospects of all selected renewable energy technologies for power generation. The results help to specify the inputs for the MARKAL optimization program as well as for future studies.

3.1 Selection of renewable energy forms and the used technologies

Whereas fossil energy sources are fixed in stock, renewable energy sources are not limited, but usually are not in ready-to-use forms for power generation. To convert renewable energy into electricity, energy-converting systems are needed. Therefore, the potential renewable energy is dependent on the technical ability of this conversion system. There are many technologies that can be used to harvest renewable energy, but not all of them appear promising. Based on the availability of renewable energy sources, specific conditions, and the technology level in Bangladesh, the present study focuses on renewable energy sources for which commercial technologies exist for power generation (Table 3.1).

Table 3.1: Selected renewable energy technologies

Renewable resource	Technology
Solar	Solar home system (SHS) Hybrid system Grid-connected solar photovoltaic (PV)
Wind	Grid-connected wind turbine
Biomass	Direct combustion Gasification
Hydro	Large hydro plant Small hydro plant

3.2 Selected renewable energy and related technologies

3.2.1 Solar energy

The energy from sunlight reaching the earth is a huge potential that can be exploited and used for generating electricity. Among several available technologies, solar PV is the most promising. PV technology converts sunlight into direct current (DC) electricity. When light falls on the active surface of the solar cell, electrons become energized and a potential difference is established, which drives a current through an external load. The central issue with PV technology is cost. The unit cost of PV has sunk in several orders of magnitude while the efficiency is continuously being improved (Brown and Hendry 2009; Gottschalg 2001; Green 2004; Ramana 2005; Van der Zwaan and Rabl 2003). Solar PV is becoming more and more popular owing to high modularity, no requirement for additional resource (e.g., water and fuel), no moving parts and low maintenance required.

Over the last two decades, the cost of manufacturing and installing solar PV system has decreased by about 20 % for every doubling of installed capacity (Brown and Hendry 2009). The solar industry has grown at a rate of 35 % per year over the last ten years (BP 2010).

Grid-connected solar photovoltaic

Different types of grid-interactive systems are being tested in countries where extensive utility grid lines are available. A PV array is connected and synchronized to the grid using an appropriate power conditioning sub-system that converts the DC energy to alternating current (AC) energy synchronized to the grid energy (Mukherjee and Chakrabartii 2007). Therefore, no additional energy storage is necessary. The grid itself is the storage medium for such a grid-interactive system, which delivers energy to the grid as long as enough sunshine is available. The system is usually integrated directly into structural elements of buildings (roof, facade). Therefore, the system has the following advantages (RETScreen 2005):

1) It reduces both energy and capacity losses in the utility distribution network, as the electric generators are located at or near the site of the electrical load.
2) It avoids or delays upgrades to the transmission and distribution network where the average daily output of the PV system corresponds with the utility's peak

demand period (afternoon peak demand during summer as a result of loads from cooling).

3) It is cost competitive, since the savings for building material is considered, i.e., no roof tiles are needed when solar panels are installed.

In recent years, rapid development in grid-connected building-integrated PV systems is due to the government-initiated renewable energy programs aiming at the development of renewable energy applications and reduction of GHG emissions. This type of solar PV system is preferred as far as PV installations are concerned. Germany introduced a "100,000 roofs program" (Erge et al. 2001). The Japanese 70,000 roofs program started in 1994 and dominated the market for the rest of the 1990's (Brown and Hendry 2009). A PV system dissemination program has been very successful in USA, and its 1 million solar-roof initiative is going well (Yang et al. 2004). Grid-connected PV systems thus took off in the mid-to-late 1990's and since then have been the dominant application (Brown and Hendry 2009).

Solar Home System

The system consists of a 20 - 100 watt peak (Wp) PV array[1], a rechargeable battery and a charge controller. Both the array size and sunlight availability determine the amount of electricity available for daily use (WB 1996). With an appropriate sunlight regime, the system has proven to be competitive for remote households. The SHS is thus implemented in many developing countries. In Bangladesh, by the end of 2008 a total of about 350,000 SHSs had been installed (IDCOL 2008).

Hybrid system

When renewable energy technologies are used in decentralized and remote areas, they can be coupled with diesel generators to improve the total system reliability. Wind-diesel generator-battery, wind-solar PV-diesel generator-battery, PV-diesel generator-battery hybrid can be used for generating electricity in the rural areas of Bangladesh.

[1] The capacity of a PV module is defined in terms of peak of output (in watts (Wp)). The rated peak output is measured under standard test conditions of 1000 watts per m^2 solar radiation, and 25^o C cell temperature. SHSs are often designed to be smaller than 20 Wp and larger than 100 Wp.

3.2.2 Wind energy

The energy from continuously blowing wind can be captured using wind turbines that convert kinetic energy from wind into mechanical energy and then into electrical energy (Figure 3.1). Electricity generated by wind turbines can feed to the central grid or be locally consumed using small stand-alone wind turbines. Grid-connected wind turbines are the subject of this study.

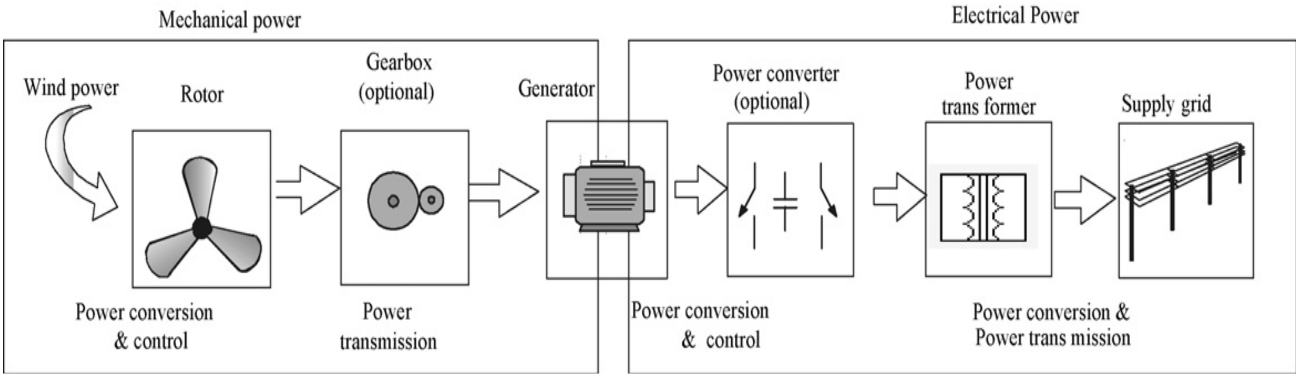

Figure 3.1: Main components of wind turbine system (Chen and Blaabjerg 2009)

Grid-connected systems

Two types of grid-connected systems can be distinguished. In the first type, the system's main priority is to cater for the local electricity demand, and any surplus generation will be fed to the grid. When there is a shortage, electricity is drawn from the grid. The other option is the utility scale, where decentralized stations are managed by the utilities in the same way as large electric power plants. Some of the important features of the grid systems are as follows (Kaundinya et al. 2009):

1) A grid-connected system is an independent decentralized power system
2) The operational capacity is determined by the supply source
3) Due to supply-driven operation, the system may have to ignore the local demand when the supply source is not available
4) The system can be either used to meet the local demand and surplus can be fed to the grid, or may exist only to feed the grid
5) The connectivity to a grid enables setting up relatively large-scale turbines.

Suitable grid-connected wind systems need to satisfy several geographical and technical conditions, e.g., high average annual wind speed, easy access to the power distribution grid, and low turbulence. Wind turbines for grid-connected systems are the most highly demanded on the market and increased by 30 % per year between 1998 and 2008 (BP 2009). The technology of these turbines and grid systems are becoming increasingly well developed and their costs have dropped significantly (Neij 1999).

3.2.3 Biomass

Biomass covers all kinds of organic matter from fuel wood to marine vegetation. Biomass is the fourth largest source of energy worldwide and provides basic energy requirements for cooking and heating of rural households in developing countries.

Energy generation using biomass offers a promising solution to environmental problems by reducing the emission of common greenhouse gases. A wide range of options exists for conversion of biomass into energy such as heat energy and electrical energy. Two widespread technologies are direct combustion and gasification.

Direct combustion involves the oxidation of biomass with excess air, producing hot flue gases which in turn produce steam, which is used to generate electricity. In a condensing steam cycle only electricity is produced, while in an extracting steam cycle both electricity and steam are generated (DOE 1997).

Gasification involves conversion of biomass to produce a medium or low-calorific gas. The gained gas is then used as fuel in combined cycle power generation plants. Being produced in combined cycle power plants, electricity from this technology has higher efficiency and is more competitive than that from a steam turbine.

Biogas is a mixture of CH_4 (40 – 70 %), CO_2 (30 – 60 %) and other gases (1 – 5 %) produced from animal dung, poultry droppings and other biomass wastes in specialized bio-digesters (Rehling 2001). This gas is combustible and can be used to generate electricity.

3.2.4 Hydro energy

Kinetic energy from flowing or falling water is exploited in hydropower plants to generate electricity. Hydropower plants are divided into two categories: 1) Large hydropower plants (>10 MW), usually with reservoirs, that cannot only produce electrical energy continuously but also are able to adjust their output according to electricity demand and 2) small hydropower plants (<10 MW) that are less flexible with respect to load or demand fluctuation due to their dependence on the water resource. Hydropower technologies are mature and widely available.

3.3 Assessment of renewable energy potential in Bangladesh

3.3.1 Definition of energy potentials

Renewable energy potentials are classified into four different categories (Voivontas et al. 1998):

1) Theoretical potential refers to the total energy available for extraction in a defined region without consideration of technical restrictions. Therefore, due to energy forms such as solar and wind energy, the theoretical potential is huge.
2) Available potential refers to the part of the theoretical potential that can be harvested easily without causing impacts on the environment.
3) Technical potential refers to the amount of energy that can be exploited using existing technologies and thus depends on the time point of assessment. This potential is used as input to the MARKAL model.
4) Economic potential refers to the amount of potential energy that is economically viable by currently given technologies. Infrastructure or technical constraints and economic aspects define the limits for the economic potential. Therefore, the economic potential depends on the costs of alternative or competing energy sources. The economic potential is assessed by MARKAL

3.3.2 Solar energy resource potential and prospects

Bangladesh is situated between 20.30° and 26.38° north latitude and 88.04° and 92.44° east longitude with an area of 147500 km^2, which is an ideal location for solar energy utilization. Estimation of the technical potential of solar energy in Bangladesh is done using the GIS-based GeoSpatial Toolkit and National Aeronautics and Space Administration (NASA) Surface Meteorology and Solar Energy (SSE) data. The GeoSpatial Toolkit is one of the tools of the solar and wind energy resources assessment application developed by the United Nations Environmental Program project funded by the Global Environmental Facility. First, the theoretical potential of the solar resource is estimated based on the availability of data on solar irradiation and land area. This potential is then converted into technical potential by introducing social and technical constraints. Social constraints mainly concern the identification of suitable locations for installation of solar energy technology. Technical constraints concern the characterization of exploitation technologies and the organizational setting conditions that have to be satisfied in the implementation of renewable energy technology projects.

Theoretical potential

The GeoSpatial Toolkit provides the solar map of Bangladesh and it shows that the solar radiation is in the range of 4 - 5 $kWh/m^2/day$ on about 94 % of Bangladesh (Figure 3.2). Data on average sunny hours per day (Figure 3.3) and monthly solar radiation (Figure 3.4) were taken from NASA for 14 widely distributed locations in Bangladesh using the Hybrid System Optimization Model for Electric Renewables (HOMER) software. The average sunny hours per day are 6.5, and the annual mean solar radiation is 0.2 kW/m^2. This indicates that Bangladesh theoretically receives approximately 69751 TWh of solar energy every year, i.e., more than 3000 times higher than the current (2006) electricity generation in the country. However, in the course of exploitation, constraints such as land use, geographical area and climate are encountered. In addition, several of solar energy technologies are limited by different factors. For detailed information, it is therefore necessary to examine the potential of solar energy from the viewpoint of a specific application.

Technology selection

Different solar energy technologies are available on the world market. Three technologies that seem to be the most suitable for Bangladesh, namely grid-connected solar PV, SHS and hybrid systems (solar, wind and diesel generator) are focused on in this study.

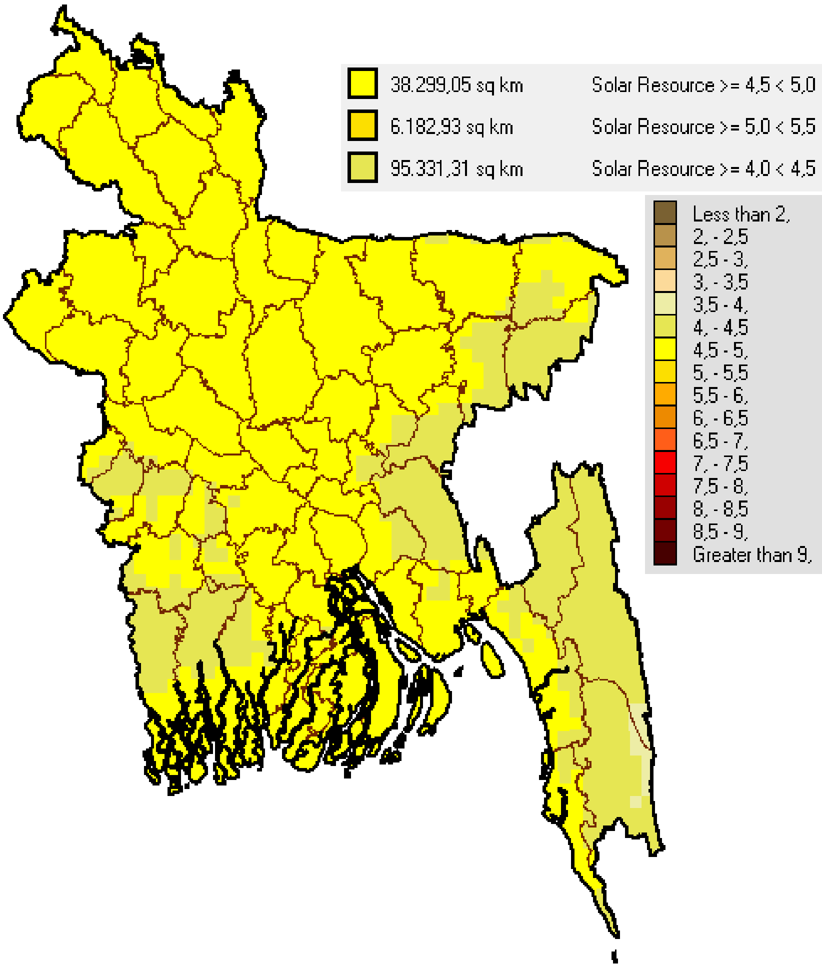

Figure 3.2: Solar radiation (kWh/m^2/day) and area of Bangladesh with highest potential for solar energy utilization

Technical potential

The average annual power density of solar radiation is typically in the range of 100 – 300 W/m^2. Thus, with a solar PV efficiency of 10 %, an area of 3 – 10 km^2 is required to establish an average electricity output of 100 MW, which is about 10 % of a large coal or nuclear power plant (Van der Zwaan and Rabl 2003). Unlike other energy conversion technologies, solar energy technologies cause neither noise, nor pollution; hence they are often installed near consumers to reduce construction costs. Thus, identification of suitable locations for application of solar energy is practically the search for suitable rooftops and unused land. A study suggests that 6.8 % (10,000 km^2) of the land in Bangladesh is necessary for power generation from solar PV to meet the electricity demand (Islam and Huda 1999). Another study states that the total household roof area is about 4670 km^2 (ADB 2003) which is about 3.2 % of the land area. In urban areas (Dhaka city), 7.86 % is suitable for solar PV electricity generation (Kabir et al. 2010).

Considering the grid availability, only 1.7 % of the land in Bangladesh is assumed technically suitable for generating electricity from solar PV (Sorensen 2001). The capacity of grid-connected solar PV is derived using the annual mean value of solar radiation (200 W/m^2) and a 10 % efficiency of the solar PV system. Thus, the technical potential of grid-connected solar PV in Bangladesh is calculated as about 50174 MW. In this study, a competitiveness analysis of solar PV with conventional power is done by the MARKAL software.

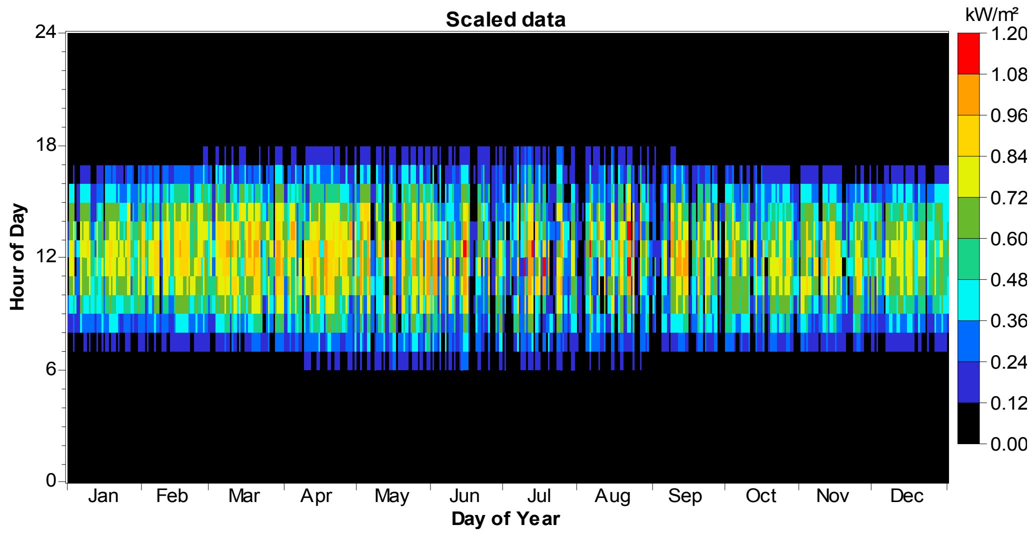

Figure 3.3: Monthly average sunshine hours in Bangladesh

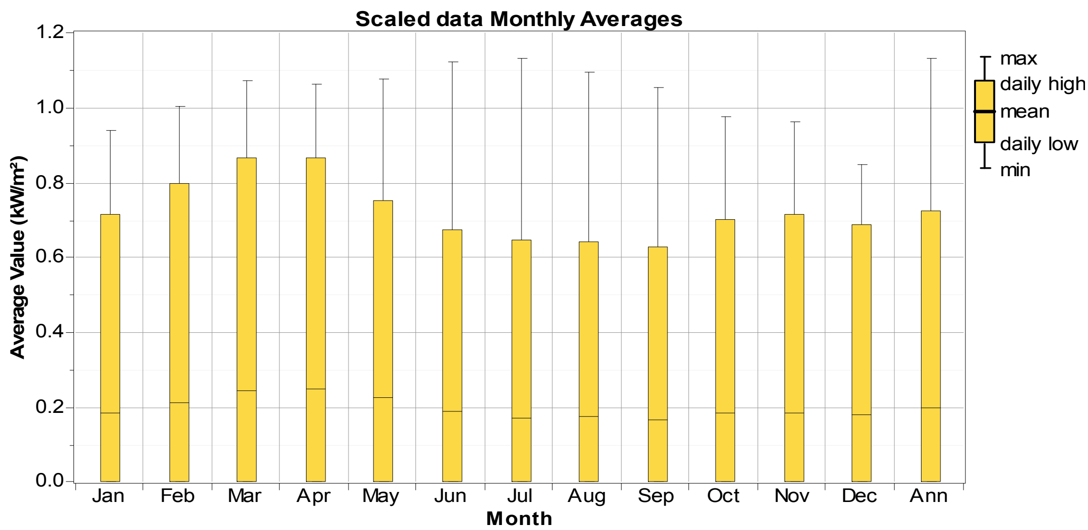

Figure 3.4: Monthly average solar radiation in Bangladesh

Whereas the potential market for grid-connected PV systems is in the densely populated urban and electrified areas, the potential market for SHSs is households without access to the national grid network, especially those in remote and mountainous areas. According to a survey report, a market of SHSs of approximately 0.5 million households reaching 4 million in the future is envisioned in Bangladesh (Khan et al. 2005). Considering an average standard 50-Wp solar panel for each household (Mondal 2005), the technical total capacity will be equivalent to 200 MW. The same capacity is applicable for the hybrid system, as this system is suitable only for rural non-electrified remote areas. Economic viability of SHS was discussed in (Mondal 2010) and techno-economic analysis of hybrid system was explained in (Mondal and Denich 2010).

Prospects for solar photovoltaic

There are many factors that can make solar PV more competitive in the future.

Costs of solar PV

The development of the cost scenario of solar PV is very important as a parameter, as it determines its market penetration in developing countries like Bangladesh. Most products show a decrease in unit cost with increased manufacturing experience. The cost of PV decreased from several hundred US $ /Wp in 1970 to about US $ 5 - 6 /Wp in the mid 1990s (Islam 2005). In an idealized model, the costs progress as a constant learning curve. The prospects for solar PV are revealed when extrapolating the historical learning cost curve, which shows a learning rate of 20.2 %. The recent funding initiatives on PV deployment will lead to an increase in experience, and this will likely lead to a significant drop in prices. At the current speed of market increase, it can be estimated that the price will drop about 20 % every 4 years (Gottschalg 2001).

Efficiency

The current efficiency is far below the theoretical efficiency. This indicates sufficient room for the improvement of solar PV efficiency. A survey of the nominal efficiency of first generation commercial modules gave a range of 10 – 15 % (Green 2004). The efficiency of a crystalline silicon cell increased from 13 % in 1976 to nearly 32 % in 1992 (Ramana 2005). During the same period, typical module efficiency rose from 7 –

8 % to 10 – 13 %. The latest multi-junction concentrating PV cells offer even higher efficiencies. The present positive development of the industry is helping to stimulate the introduction of improved manufacturing techniques and technology. The second generation of solar PV, which is more competitive, is expected to appear over the coming decade (Green 2004).

Limited fossil resources and increasing prices

The depletion of fossil fuels is occurring at a fast rate due to the growing gap between the demand and production of fossil fuels (Mukherjee and Chakrabartii 2007). At the same time, these fuels experience an opposite trend to that of solar PV, e.g., the price for produced electricity is increasing due to the increase in the price of fossil fuels and environmental damage costs, e.g. externality cost for CO_2 emissions.

3.3.3 Wind energy resource potential and prospects

Technical potential of grid-connected wind turbines

Assessment of the wind energy resource and the installation of wind energy conversion systems in Bangladesh have long been hindered due to lack of reliable wind speed data. There is no reported wind map of Bangladesh that could be relied upon and used for wind energy assessment (Khan et al. 2004). One of the very first steps towards harnessing energy from the wind is to make an extensive assessment of the wind energy potential and a cost analysis for a site of interest. In this study, a competitiveness analysis of wind power with conventional power is done by the MARKAL software.

First, the theoretical potential of wind energy is estimated by developing a Bangladesh wind map. This is possible using a reference wind turbine and available wind speed data. The technical potential is then assessed by introducing restrictions grouped as social and technical constraints. The definition of social constraints enable elimination of areas not suitable for the exploration of the wind energy potential such as high latitude, restricted and protected areas, and residential areas. Technical constraints define basic conditions for the operation of wind turbines such as arrangement of wind turbines and the minimum wind velocities (Nguyen 2007b). In this study, a NASA SSE data set (SSE 2009) is used to develop a wind map of Bangladesh to determine potential sites for wind energy exploration. Then a reference wind turbine is used to find the power density. Candidate sites are estimated based on the developed wind map. Finally, constraints were applied for the technically potential area, which was converted to the total technical potential of wind energy for Bangladesh.

Unlike surface measurements, the NASA SSE data set consists of a 10-year global average on a 1° by 1° (about 100 km x 100 km) grid. The SSE data, which are essentially an average over the entire area of the cell, may not represent a particular site within the grid. However, this database is an excellent and easy to use source, which could be used for any preliminary study for renewable energy resource estimation (Khadem and Hussain 2006; Khan et al. 2004).

One set of wind speed data for 50 m height was gathered for 20.5° N – 26.5° N and 78.5° E – 92.5° E. Based on these data, the Bangladesh wind map was developed for the theoretical potential (Figure 3.5). The only coastal regions appear as high wind areas when compared with the main land.

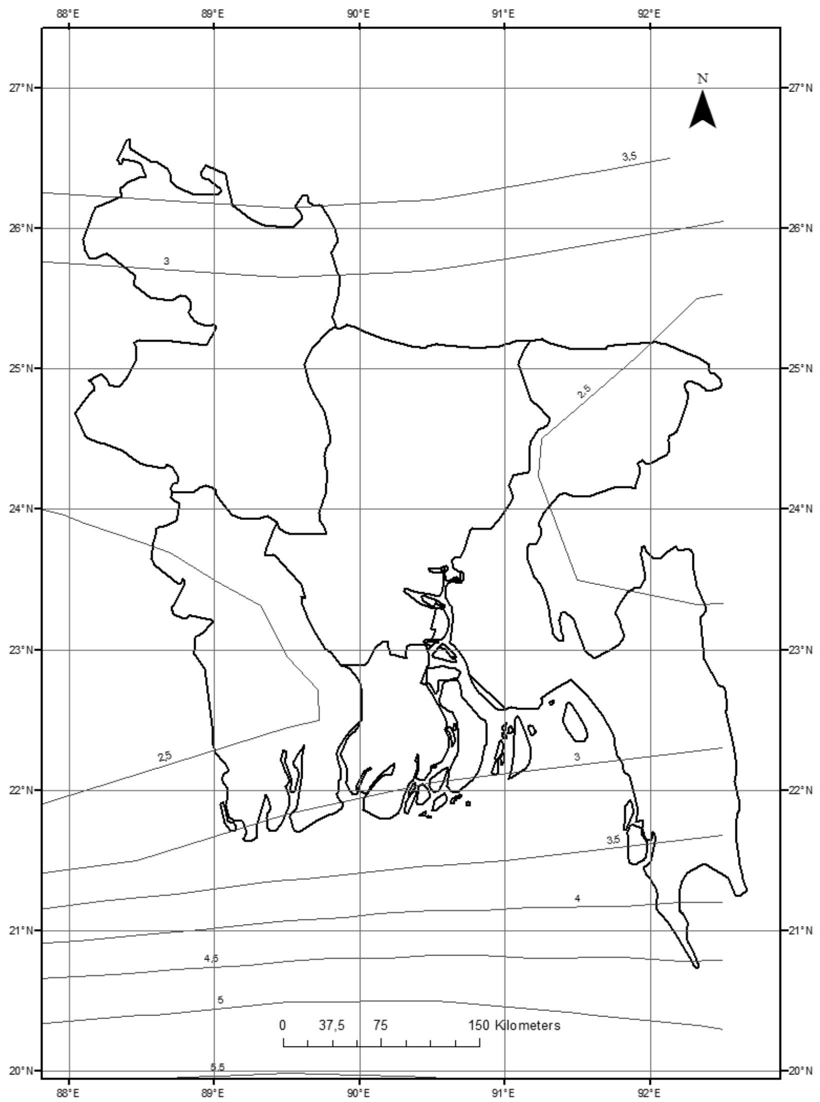

Figure 3.5: Wind map of Bangladesh at 50 m height using NASA SSE data set (m/s)

Selection of wind turbine

To find the technical potential of wind energy it is necessary to have a reference wind turbine so that a theoretical power output corresponding to each wind speed value can be calculated. This wind turbine should suit the local conditions, including the local possibility of manufacturing accessories. Furthermore, road conditions, the availability of suitable mobile cranes or trucks are the other important factors that also should be paid attention to (Nguyen 2007b).

Considering the above requirements, a wind turbine of 330 kW from Enercon (E33) was selected (Table 3.2). From the power curve (Figure 3.6), it can be observed that E33 starts operation at a cut-in wind speed of 3 m/s. Beyond 13 m/s rated power, output remains constant. Cut-out wind speeds are those higher than 25 m/s.

Table 3.2: Specification of Enercon wind turbine E33

Technical parameter	Value
Rotor diameter	33.4 m
Swept area	876 m^2
Rated power	330 kW
Starting wind speed	3
Rated wind speed	12 m/s
Cut out wind speed	28-34 m/s
Generator	Synchronous
Number of blades	3
Tower height	50 m

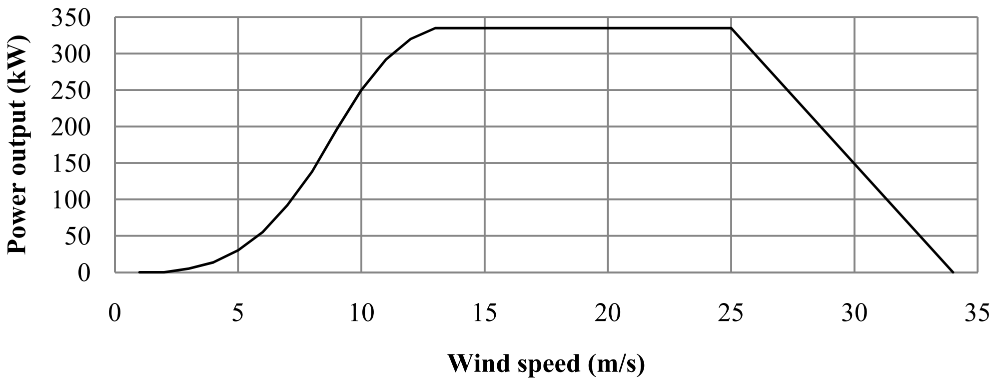

Figure 3.6: Power curve of E33-330 kW wind turbine (ENERCON 2007)

Calculation of energy output

The HOMER optimization tool was used to find the total energy output of the wind turbine. The Weibull distribution function is mostly used to represent the distribution of wind. HOMER uses the distribution function as:

$$f(v) = \left(\frac{C}{A}\right)\left(\frac{V}{A}\right)^{c-1} \cdot \exp\left(-\left(\frac{V}{A}\right)^{c}\right) \tag{3.1}$$

where $f(v)$ = Weibull probability function for wind speed v, C = shape parameter, which typically ranges from 1 to 3 (Bala 2003).

For a given average wind speed, the higher the shape parameter is, the narrower the distribution of wind speed around the average value. Because the wind power varies with the cube of the wind speed, a lower shape parameter normally leads to higher energy production at a given wind speed. A = scaling parameter. When C equal to 2, the Reyleigh function represents well enough the real wind speed distribution and it is then possible to derive the wind speed distribution if only yearly average wind speed is known. In HOMER, C equal to 2 and yearly average wind speed are used.

Finally, HOMER calculates yearly energy production applying logarithmic or power low profile with standard temperature and pressure, and air density. With the distribution function and power curve, the yearly energy production (YEP) is calculated by HOMER by integrating the power output at every bin width using the following equation:

$$YEP(v_m) = \sum_{v=1}^{v=25} f(v) \cdot P(v) \cdot 8760 \tag{3.2}$$

where v_m = average wind speed, $P(v)$ = turbine power at wind speed v, $f(v)$ = Weibull probability function for wind speed v, calculated for the average wind speed v_m.

To calculate the hours per year with full power, the energy production is divided by reference turbine rated power. Figure 3.7 depicts the theoretical potential of wind energy output for Bangladesh in the form of hours with full power.

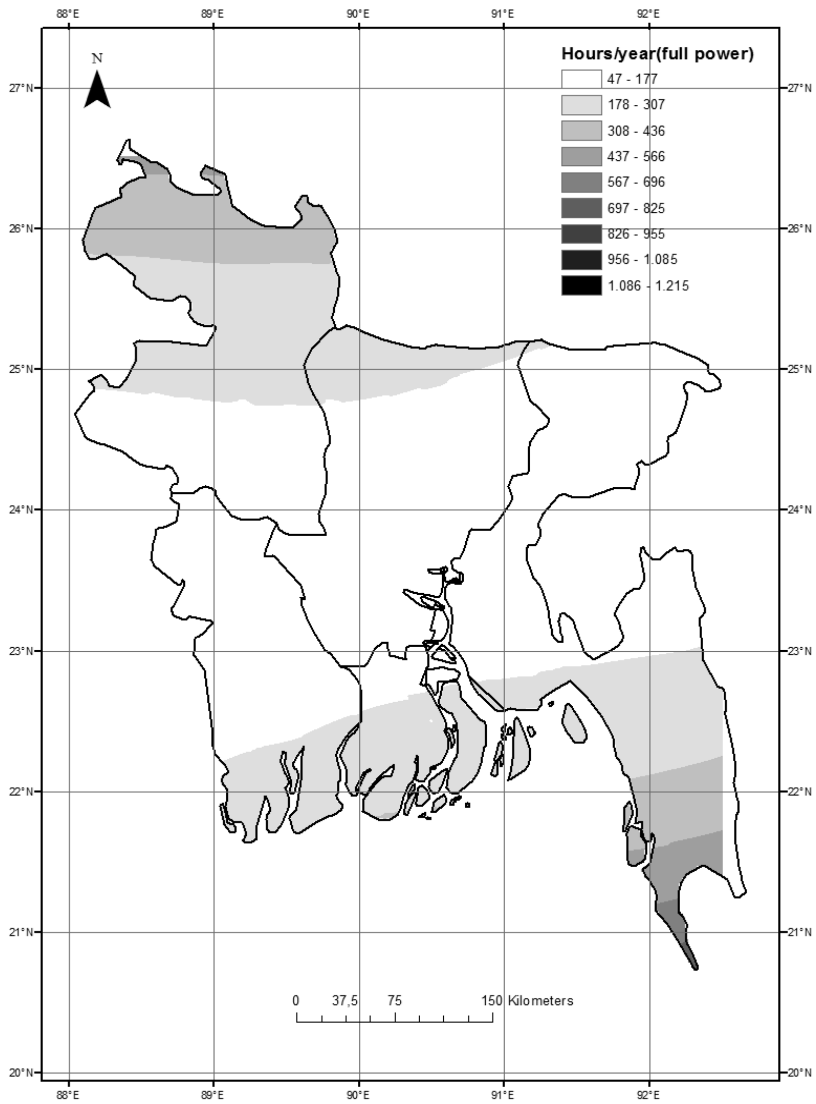

Figure 3.7: Theoretical potential of wind energy in Bangladesh

Technical potential

For an infinite number of wind turbines with 10 rotor diameters (10D) spacing, the limited array efficiency is about 60 %. For a finite number, average losses are much lower, and closer sitting is more practical (Grubb and Meyer 1993). For the case of the Bangladesh coastal area, finite or limited numbers of turbines are applicable. For simplicity, the present study takes 4D as the standard distance between two wind turbines. Thus, the area requirement for each E33 turbine will be 14016 m^2 and as a result, wind turbine density will be 23.5 MW/km^2.

Assuming that less than 1000 hours of full power is the feasible threshold for the exploitation of wind energy, the areas that satisfy this condition in Bangladesh would be sufficient for the installation of 4614 MW of wind power (Due to limited grid access and the scattered area, only 2 % of this area is considered technically potential). Due to limited wind resource potential, which is only in the coastal regions, stand-alone wind turbines are not considered in this study.

Future prospects for wind energy

In 2002, over 32 GW and in 2008 over 122 GW of wind capacity were installed worldwide (BP 2009; DeCarolis and Keith 2006). Although wind energy currently represents about 0.1 % of total electricity (Sims et al. 2003), it has the fastest relative growth rate of any electricity generating technology. Along with the increasing exploitation of wind energy, the cost of wind turbines dropped dramatically by 52 % between 1982 and 1997 (Neij 1999). The Danish energy agency predicts that a further cost reduction of 50 % can be achieved by 2020 (Ackermann and Soder 2002). Therefore, with increasing energy costs for conventional technologies and increasing environmental costs, wind power is becoming more and more attractive.

3.3.4 Biomass potential and prospects

Biomass energy is mainly from fuel wood, agricultural residues, animal dung and municipal solid wastes (MSW), the availability of which is linked with forestry resources, crop production, animal numbers and urban waste production. First, total biomass production is estimated and then the energy potential is estimated by applying the individual recovery rate, residue to yield ratio (for agricultural residues only), moisture content and calorific value.

Agricultural residues

Approximate land use for agriculture is 55 % of the total land area of Bangladesh (Islam et al. 2008). Agricultural residues from major crop residues such as straw and husks from rice plants, bagasse from sugarcane and jute tick contribute significantly to the biomass sector. There are two types of agricultural crop residues: field residues and process residues. Field residues are residues that are left in the field after harvesting and generally used as fertilizer. Process residues are generated during crop processing and are available at a central location.

Studies in neighboring Asian countries (Bhattacharya et al. 1999; Elauria et al. 2006; Koopmans 1998; Perera et al. 2006) produced useful residue to yield ratios for several agricultural crops. These ratios are used in this study together with published productivity figures for the individual crops (Table 3.3). It has been considered that only 35 % of field crop residues can be removed without adverse effects on the future yields. Crop processing residues, on the other hand, have a 100 % recovery factor (Hossain and Badr 2007). In this study, only process residues are considered, as field residues are used for other purposes (Table 3.4). It is estimated that the total annual amount of recoverable agricultural crop residues is 44.1 million tons (mton), of which 60 % are field residues and the remaining are process residues.

Wood fuel

Total wood fuel supply and consumption in Bangladesh were projected at 8.9 mton and 9.4 mton, respectively, in 2004 (FAO, 1997). 1.428 mton (16 %) wood fuel comes from deforestation. Domestic cooking uses 63 %, and the rest goes to industry and the commercial sectors (Islam 2002). Most of the fuel wood consumed by rural households is supplied by the homestead trees, and mainly consists of firewood, twigs and leaves. Estimates for the rate of supply of tree residues in recent years are not available. Total tree residues in 1992 were 1.8 mton (Hossain and Badr 2007). Both wood processing residues and recycled wood are an important source of energy. In 1998, 118,000 tons of sawdust was available for energy purposes (Moral 2000). Considering the 100 % recovery rate and the unchanging production rate, the annual amount of recoverable biomass from forests and the forestry industry in Bangladesh is about 10.9 mton. On the other hand, FAO (1997) found that the future projection of demand and supply of wood fuel is bleak. For this reason, in this study wood fuel is not considered for power generation.

Table 3.3: Annual agricultural crop production in 2003 (Hossain and Badr 2007)

Crop	Annual production (10^3 ton)
Rice	39090
Sugarcane	6838
Vegetables (total)	1837
Wheat	1507
Jute	792
Pulse	345
Coconut	88
Millet	57
Groundnut	45
Maize	10

Municipal solid waste

Rapid urbanization and population growth are mainly responsible for the rapidly increasing rate of municipal solid waste (MSW) generation in the urban areas of Bangladesh. The per capita waste generation and calorific value of various waste components are the most important data for calculating the potential of MSW to generate electricity. It has been found that in Dhaka city, the per day waste generation rate varies from 4000 to 5000 tons (JICA 2005; Khatun 2008; PREGA 2005). Different studies have found that per capita waste production ranges from 0.4 kg/day to 0.71 kg/day. In other large cities, it varies from 0.36 kg/day to 0.43 kg/day (Alamgir and Ahsan 2007). This is comparable to an average per capita MSW generation rate of 0.3 kg/day and 0.57 kg/day in two Indian cities namely Kanpur and Calcutta, respectively (Mukherjee and Chakrabartii 2007). Due to a limited MSW in other cities for generating electricity, only four major cities are considered in this study. Based on the total population of the Dhaka, Chittagong, Rajshahi and Khulna city corporations and average waste generation per capita of 0.5 kg/day, a total of 8300 tons waste are generated daily. The average recovery rate of MSW is 70 % (Alamgir and Ahsan 2007), i.e., 2.12 mton per year.

Table 3.4: Production and recoverable amounts of agricultural residues in 2003

Crop residues	Residues production ratio	Residues generation (10^3 ton)	Residues recovery (10^3 ton)
Field residues			
Rice straw	1.695	66258	23190
Wheat straw	1.75	2637	923
Sugarcane tops	0.3	2051	718
Jute stalks	3	2376	832
Maize stalks	2	20	7
Millet stalks	1.75	100	35
Groundnut straw	2.3	78	27
Cotton stalks	2.755	124	43
Residues from vegetables	0.4	735	257
Residues from pulses	1.9	656	229
Subtotal		75035	26261
Process residues			
Rice husk	0.321	12548	12548
Rice bran	0.83	3244	3244
Sugarcane bagasse	0.29	1983	1983
Coconut shells	0.12	11	11
Coconut husks	0.41	36	36
Maize cob	0.273	3	3
Maize husks	0.2	2	2
Groundnut husks	0.477	16	16
Subtotal		17843	17843
Total		92878	44104

Animal waste and poultry droppings

Manure from cattle, goats, sheep and buffaloes are the common animal waste in the country. The quantity of waste produced per livestock per day varies depending on body size, type of feed and level of nutrition. The production rates are estimated by employing the number of heads of the national herds and the waste generation rate per head for the individual species (Rehling 2001; Table 3.5). The collection factor of animal waste and poultry droppings is considered to be 50 % (Hossain and Badr 2007). Accordingly, it is estimated that the total amount of recoverable animal and poultry waste in Bangladesh per year is about 40 mton.

Table 3.5: Number of livestock and their residues (Islam et al. 2008; Rehling 2001)

Livestock	Number of heads (thousand)	Dung yield (kg/head/day)	Residues (mton/year)
Buffaloes	828	8-12	3.02
Cattle	23652	5-10	64.74
Goats	33800	0.25-0.50	4.62
Sheep	1121	0.25-0.50	0.15
Poultry	200000	0.10	7.3
Total			79.83

Theoretical energy potential from recoverable biomass resources

The total annual recoverable rate of biomass in Bangladesh is about 126 mton per year (Table 3.6). Using the lower calorific values of the individual biomass components, the total available energy potential is about 1282 PJ. Agricultural residues represent 47 % of total biomass energy.

Biomass energy available for electricity generation

It can be concluded that only rice husks, MSW, poultry droppings and bagasse are useful for electricity generation, as field residues are used for fertilizer and animal waste as a cooking fuel in Bangladesh (Table 3.6). 50 % of the rice husks are used for energy applications such as domestic cooking and steam production for rice parboiling. Therefore, theoretically only 50 % of the rice husks can be used for power generation. MSW and bagasse can be used to 100 % for grid power generation, as sugar mills are connected to the grid network. Zaman (2007) found that only 57 % of poultry droppings are viable for small-scale power generation (Zaman 2007). Techno-economic viability was assessed by the MARKAL model for power generation using rice husks, MSW, poultry droppings and bagasse.

Table 3.6: Energy potential of biomass resources

Biomass	Recovery rate (10^3 ton/year)	Moisture content (% by mass)	Lower calorific value	Energy content (PJ)
Field residues				
Rice straw	23190	12.7	16.30	329.99
Wheat straw	923	7.5	15.76	13.46
Sugarcane tops	718	50	15.81	5.68
Jute stalks	832	9.5	16.91	12.73
Maize stalks	7	12	14.70	0.09
Millet stalks	35		12.38	0.43
Groundnut straw	27	12.1	17.58	0.42
Cotton stalks	43	12	16.40	0.62
Residues from vegetables	257	20	13	2.67
Residues from pulses	229	20	12.80	2.34
Subtotal	26261			368.43
Process residues				
Rice husks	12548	12.4	16.30	179.17
Rice bran	3244	9	13.97	41.24
Sugarcane bagasse	1983	49	18.10	18.31
Coconut shells	11	8	18.53	0.19
Coconut husks	36	11	18.53	0.59
Maize cob	3	15	14	0.04
Maize husks	2	11.1	17.27	0.03
Groundnut husks	16	8.2	15.66	0.23
Subtotal	17843			239.79
Total agricultural crop residues	44104			
Other biomass				
Animal waste	72540	40	13.86	603
Poultry droppings	7300	50	13.50	49.28
MSW	2120	45	18.56	21.64
Total	126064			1282.39

The amount of agricultural residues is assumed to increase in the near future due to increased food production. The sugar industry is expected to produce more bagasse. Considering the limitation of arable land, it is assumed that the agricultural residues supply will increase at the rate of population growth of 1.5 % in the period

2005-2010 and 1 % in 2010-2015, and then will remain at the level of 2015. Similarly, poultry droppings and MSW residues are expected to increase at a higher rate due to increasing urbanization and income level. It is assumed that the MSW and poultry droppings supply will increase at a rate of 2 % from 2005-2015 and 1.5 % from 2015-2025 and then will remain at the level of 2025 (Table 3.7).

Table 3.7: Total biomass energy supply potential between 2005 and 2035 in PJ

Biomass source	2005	2010	2015	2020	2025	2030	2035
Rice husks	179	193	203	203	203	203	203
Bagasse	18	20	21	21	21	21	21
MSW	21	24	26	28	31	31	31
Poultry droppings	49	54	60	65	70	70	70

Biomass technologies and prospects for power generation

A number of technologies exist for large-scale biomass combustion. Power generation based on biomass combustion employing boiler-steam turbine systems is well established. The current global installed capacity of electricity generation from biomass is about 40 GW (Bhattacharya and Salam 2006). Biomass-based generation technology is well established in the pulp and paper industry as well as in a number of agro-industries, and there is substantial scope for improvement in efficiency. India has launched a sugar-mill-based modern cogeneration program; a capacity of 348 MW has been already commissioned. China has executed some projects for biomass based electricity generation. By the end of 2002, the total installed capacity of bio-energy power generation there was 2 GW, in which generation from bagasse was 1.7 GW, while the rest was based on crop residues, biogas, landfill gas and MSW (Bhattacharya and Salam 2006).

Bangladesh has installed 14 sugar-mill-based cogeneration plants using bagasse. Total power generation capacity is 38.1 MW (BSFIC, 1994; Sarkar et al. 2003). Bagasse is usually burned to produce steam in sugar-processing operations and to generate electricity to run the sugar mills themselves. The existing mills produce steam in boilers at 15 kg/cm^2 (Sarkar et al. 2003). Hasan (2006) found that an increase in steam pressure in boilers would provide enough steam and electricity to run a typical sugar mill (Hasan 2006). The excess electricity can be pumped into the national grid.

Average crushed-cane capacity per sugar mill is about 1400 tons/day in Bangladesh, and could generate up to 12.75 MW and in total about 178.5 MW.

In the rice processing industry in Bangladesh, there are promising prospects for new biomass technologies. The first rice-husk based off-grid power plant was commissioned in 2007. It is based on a biomass-gasifier internal combustion (IC) engine system and has a rated capacity of 250 kW. It can be estimated that a ton of rice paddy could produce 282 kg dry rice husks with a calorific value of 16.3 MJ/kg. For gasification in gas turbine systems, this residue would generate about 10.6 kW. A survey (GTZ 2008) found that 540 rice mills exist in Bangladesh, and that the capacity ranges from 30 tons/day to 120 tons/day. Counting only rice mills with a capacity higher than 30 tons/day, the technical potential of electrical power is about 171 MW.

Methods and technologies for power generation from MSW have developed gradually from traditional ones to advanced ones in the following order: landfill, mass burn incineration, fluidized bed incinerator, gasifier and plasma waste converter. The landfill gas to power technology is the most cost-effective way to deal with a large amount of waste with low calorific value. Landfill technology, as suggested by the ADB mission, seems to be the most preferred technology for Dhaka city (PREGA 2005). Dhaka city alone has a capacity higher than 5000 tons/day, and the potential power generation is about 20 MW (Khatun 2008; PREGA 2005).

The first biogas plant in Bangladesh was installed in 1972. Since then, several organizations have taken this initiative to research, develop and disseminate biogas technology in the country. Two biogas digester types are commonly used in Bangladesh, e.g., the fixed dome and floating dome type. Several government-financed biogas projects have been implemented with different degrees of success. Over 25,000 fixed-dome biogas plants have been installed and some large farms produce electricity using this technology. For heating purposes, a medium-size farm is suitable, while larger farms could also produce electricity. Poultry farms that have more than 500 birds could generate about 360 GWh per year (Zaman 2007).

3.3.5 Hydro resource potential

The scope of hydropower generation is very limited in Bangladesh. The country is mostly flat, except for some hilly regions in the northeastern and southeastern parts.

Furthermore, Bangladesh is a riverine country, and major rivers have a high flow rate for about 5 - 6 months during the monsoon season, which is substantially reduced during the winter.

Large hydropower potential

"Large hydropower" means a capacity higher than 10 MW. At present, 230 MW of hydropower are generated at the Karnafuli hydropower plant, which is the only hydro-electric power plant in Bangladesh; it is operated by the Bangladesh Power Development Board (BPDB). The BPDB is considering extension of this power plant to add another 100 MW capacity. The additional energy will be generated during the rainy season. Two other prospective sites for large hydropower plants at Sangu and Matamuhuri have been identified by the BPDB. It estimates that the potential capacity is 140 MW at Sangu and 75 MW at Matamuhuri.

Small hydropower potential

"Small hydropower" means a capacity less than 10 MW. Within this range, hydropower plants are further divided into small hydro- (>3 MW <10 MW), mini hydro- (>300 kW <3 MW), micro hydro- (>5 kW <300 kW), and pico hydro- (<5 kW) power plants that differ with respect to investment cost and annual hydropower availability (Table 3.8).

Table 3.8: Small hydropower potential (Islam et al. 2008)

Capacity range	Number of sites	Location/Region	Total capacity (kW)
Small hydro (3 - 10 MW)	14	Northeastern region	111,000
Mini hydro (300 kW - 3 MW)	11	Mainly at Teesta barrage, Rangpur and northeastern region	12,900
Micro hydro	32	Chittagong hill tracts, Sylhet, Dinajpur, Rangpur	798
Pico hydro	1	Lake Fiaz , Chittagong	4
Total			124,702

3.4 Modeling of renewable energy technologies in MARKAL

This section discusses the operation characteristics of the selected renewable energy technologies and how these are handled in the MARKAL-Bangladesh model.

Therefore, only representative and major technologies are addressed, the others that do not require special treatment will be ignored.

3.4.1 Grid-connected solar photovoltaic

In the MARKAL model, the weather-dependent performance of PV can be simulated with the table PEAK and the seasonal capacity utilization factor (CF(Z)(Y)). The table PEAK describes the portion of capacity of a certain technology that can be mobilized to meet the peak load. On the other hand, the parameter CF(Z)(Y) specifies the availability of solar PV technology during a defined season and during the day (Table 3.9). Obviously, the availability of solar energy during the summer would be higher than in the winter and absent during the nighttime. Grid-connected PV technology is modeled in MARKAL (Table 3.9). Furthermore, a 30 % upper bound[2] based on the growth rate per annum is considered in the PV modeling using the ADRATIO table (see Chapter 2). The allowed growth capacity is relatively high, but in the early years of a new technology, a growth rate of 20 – 30 % per year in the first two decades after introduction is common (Larson et al. 2003). Globally, the total installed capacity of solar PV, which was less than 1 MW in 1976, had reached 320 MW by 1997, which was a growth rate of more than 31.5 % per year (Ramana 2005).

3.4.2 Grid-connected wind power

It is well known that wind speed varies continuously with time and is very sensitive to topography. Therefore, wind energy technologies have only a limited capacity for meeting the peak load. These characteristics need to be considered in the modeling. In MARKAL, this is possible by using the PEAK and annual availability parameter (Table 3.10). As mentioned above, the table PEAK describes the portion of capacity of a certain technology that can be drawn to meet the peak load.

This study estimates that only 4614 MW could be generated from wind energy in Bangladesh. In the MARKAL-Bangladesh modeling, the availability of this resource is not constrained by the resource size but by the upper bound of possible installed wind power capacity and by a growth rate averaging 30 % per year until the end of the

[2] Upper bound refers to the limit on annual production specified in the model and is not necessarily the level at which the resource is used in the model.

analysis period. For comparison, wind electricity generation worldwide increased almost 32 % per year between 1992 and 2002 (DeCarolis and Keith 2006).

Table 3.9: Main parameters for modeling grid-connected solar PV

Parameter	Solar PV	Reference
Seasonal Capacity Utilization Factor CF(Z)(Y) • Summer daytime • Summer nighttime • Intermediate daytime • Intermediate nighttime • Winter daytime • Winter nighttime	 0.65 00 0.45 00 0.30 00	Estimated based on APEC (2002)
PEAK	0.20	APEC, 2002
Initial investment cost (million Taka*/kW)	318750	Shafiei et al. 2009
Annual fixed operation & maintenance (O&M) cost (million Taka/kW)	3085	NEA 2005
Life time (year)	30	
Minimum investment level in new capacity (MW)	20	
Introduction year	2010	

* *Bangladeshi currency (100 Taka = 1.569 USD in 2005)*

Table 3.10: Main parameters for modeling grid-connected wind power

Parameter	Value	Reference
Investment cost (million Taka/kW)	64,706	Nguyen 2007a; Rout et al. 2009
O&M cost (million Taka/kW)	1466	Nguyen and Ha-Duong 2009
PEAK	0.4	APEC 2002
Annual availability	0.3	APEC 2002
Life time	25	
Introduction year	2010	

3.4.3 Biomass technologies

The four advanced technologies for electricity generation from biomass introduced above are modeled in the MARKAL-Bangladesh (Table 3.11).

Table 3.11: Main parameters for modeling biomass based power plants (APEC 2002; DOE 1997; Hasan 2006; IDCOL 2006; Khatun 2008; PREGA 2005; Zaman 2007)

Technology	Investment cost (million Taka/kW)	O&M cost (million Taka/kW)	Efficiency (%)	Introduction year	Life time (year)	Upper bound by 2035
Rice-husks-based power plant	91800	5227	22.67	2010	20	100
Biogas-based power plant	157781	18900	25	2010	20	100
Bagasse-based power plant	35700	2231	22.67	2010	20	200
MSW-based power plant	71655	2805	25	2015	20	200

3.4.4 Hydropower

Due to the nation's flat terrain and potentially large social and environmental impacts, further exploitation of hydropower is expected to be limited (Uddin 2006). The estimated exploitable capacity for hydropower generation is 745 MW, of which around 200 MW is by small- and mini-sized hydropower plants (Wazed and Ahmed 2008). In 2005, the total installed capacity of hydropower plants was 230 MW. It is assumed that a 100-MW extension of the Karnafuli hydropower plant will be added in 2015. The maximum capacity of hydropower is considered only after 2020 for this analysis. Water availability for operation of hydropower plants depends on the season, and this is included in MARKAL as an important factor, which is controlled by two parameters, namely ARAF and SRAF (Loulou et al. 2004). Parameter ARAF describes the maximum annual availability factor for the power plant, while parameter SRAF (Z) indicates seasonal reservoir availability in season Z (Table 3.12).

Table 3.12: Main parameters for modeling hydropower plants in MARKAL

Technology	Investment cost (million Taka/kW)	Fixed O&M cost (million Taka/kW)	Variable O&M cost (million Taka/PJ)	Introduction year	ARAF	SRAF in summer
Existing Karnafuli hydropower plants	95625	443	10	2005	0.43	0.7
Large plants	95625	443	10	2015	0.43	0.7

4 ELECTRICITY DEMAND PROJECTION

The MARKAL optimization tool requires energy demand figures for the period under study. The objective of this section is to project the electricity demand using an accounting-type energy modeling and planning software. The Long-range Energy Alternative Planning (LEAP) tool was used to calculate the demand for the different sectors up to the year 2035 considering the base year 2005. LEAP is used to develop different electrical demand projections based on different gross domestic product (GDP) growth scenarios namely low GDP growth, average GDP growth and high GDP growth scenarios, as the relationship between energy consumption and economic growth has been widely discussed in the energy economics literature. The scenarios in LEAP are generated to encompass the main factors that are anticipated to change over time. The LEAP projections are used to provide inputs related to energy demand in the MARKAL model to compute the least-cost options for the Bangladesh power sector.

4.1 Energy demand

The total commercial energy availability in Bangladesh increased from nearly 366 PJ in 1995 to around 1036 PJ by the year 2005 (BBS 2008; Islam 2001a). This implies an annual growth of 11 %. Natural gas is the only significant indigenous commercial energy resource in Bangladesh. In 2000, 46.5 % of the final energy demand was provided by gas, while the remaining demand was met by petroleum products (47.52 %), electricity (5.8 %) and coal (0.2 %). In 2005, the consumption of final energy was dominated by imported petroleum products, which accounted for 47.3 %. The share of gas, electricity and coal was 46.4 %, 5.7 % and 0.2 %, respectively (BBS 2008).

Commercial energy consumption can be divided into six different sectors namely domestic, commercial (service), transport, non-energy use[3], agriculture and others. The agricultural sector consumption share increased sharply from 8.3 % in 2000 to 11.4 % in 2005 (Figure 4.1). The consumption in the domestic, transport and commercial sectors also increased slightly. Non-energy use (e.g., use of gas for fertilizer

[3] Non-energy use indicates use of natural gas as raw material in fertilizer factories and consumption of energy carriers

production) and final consumption of commercial energy in the industrial sector decreased in 2005 compared to 2000.

Non-commercial sources of energy such as fuel wood, animal dung and agricultural residues constitute the major share of the gross energy demand in the country. Estimated primary energy supplied by non-commercial energy was 335 PJ in 1995 and 446 PJ in 2005 (BBS 2008). The annual growth rate was less than 3 %. The final energy share of biomass was 69 % and 60 % in 1995 and 2000, respectively (Imam 2005; Islam 2001b). The percentage of non-commercial energy is continuously decreasing with time, which is a reason for the increasing percentage of commercial energy consumption.

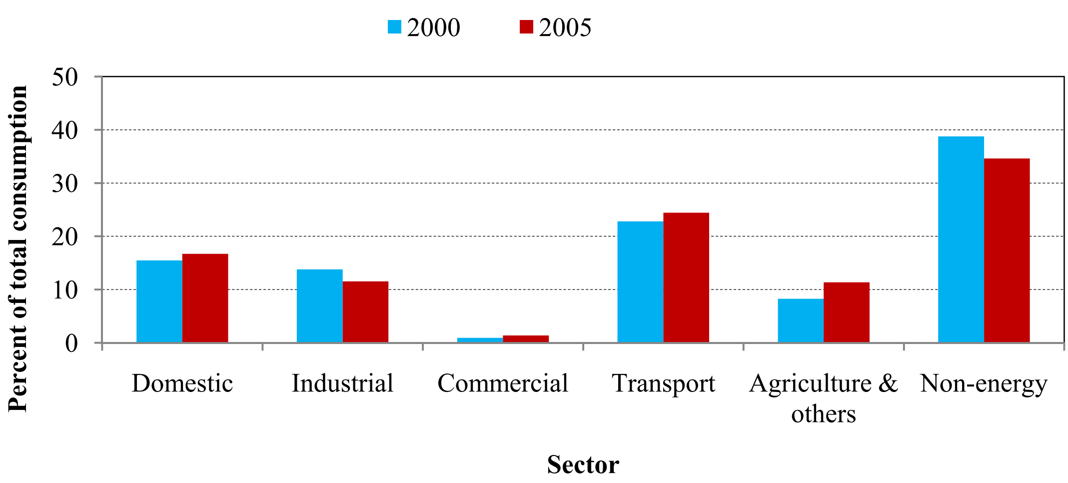

Figure 4.1: Sector wise break-up of commercial energy utilization

4.2 Electricity demand: Trend and projection

Electricity demand is divided into six categories namely agricultural, industrial, rural residential, urban residential, commercial and other sectors. Each of these sectors of the economy shows a typical trend with respect to the growth in energy demand. The demand for electricity in Bangladesh has always been higher than the supply, which has led to shortage of power. Shortage of power has shown an increase over the past few years, as the increase in demand has grown more rapidly than the generation of power.

In this section, electrical demand scenarios of Bangladesh are developed. These scenarios are driven not only by GDP growth, but also by population, household number or energy intensity (energy use per activity). The scenarios are generated to encompass any factor that is anticipated to change over time. The main objective of this projection is to achieve a rapid and sustainable development of the Bangladesh power sector.

4.2.1 LEAP methodology

LEAP is an accounting-type energy planning model. In a bookkeeping fashion, it calculates the energy requirement of the demand sector from year to year by multiplying the activity (energy service) by the energy intensity for all end uses. The prediction of the growth rates of activities or energy intensity is exogenous to LEAP. The demand program uses the end use driven approach. The data is assembled in a hierarchical format based on four levels; sector level (residential, industrial etc.), sub-sector levels such as rural or urban, further end-use (lighting, cooling, etc.) and finally end-uses according to devices (fluorescent lamp, compact fluorescent lamp, etc.) or according to fuel use (diesel, electricity, etc.). In the energy demand program, the energy intensity values along with the type of fuel used in each device are required to estimate the energy requirements at sector, sub-sector and end-use level.

Projections for electricity utilization in households and in the industrial, commercial and agricultural sectors are made over a long-term planning horizon (2005 – 2035). The effects of the key variables population, number of households, electrification levels, GDP share (mainly for industry, commerce and agriculture) by sector based on three different GDP growth scenarios (discussed in the following section) are assessed in LEAP. For the urban and rural residential (household) sectors, end-use methodology combined with trend analysis is used for electricity demand projection. The energy intensity per electrified household is applied in the residential sector; energy intensity per unit of GDP is applied for the other sectors (applied tree structure in Figure 4.2).

A demand analysis is performed for the household sector for a particular activity, i.e., lighting, refrigeration, cooling (fan and air conditioning) and other end-use devices (TV, radio, computer, etc.). The total electricity consumption per household for the current account is calculated based on total consumption in the household sector and total electrified number of households. Twelve-year historical data (1994 – 2005) are used for projections based on different scenarios. The energy intensity for all sectors (except residential sector) is calculated on the basis of quantity of energy used per year and the GDP value for this specific sector in that year. In this analysis, energy intensity is in kWh/Taka.

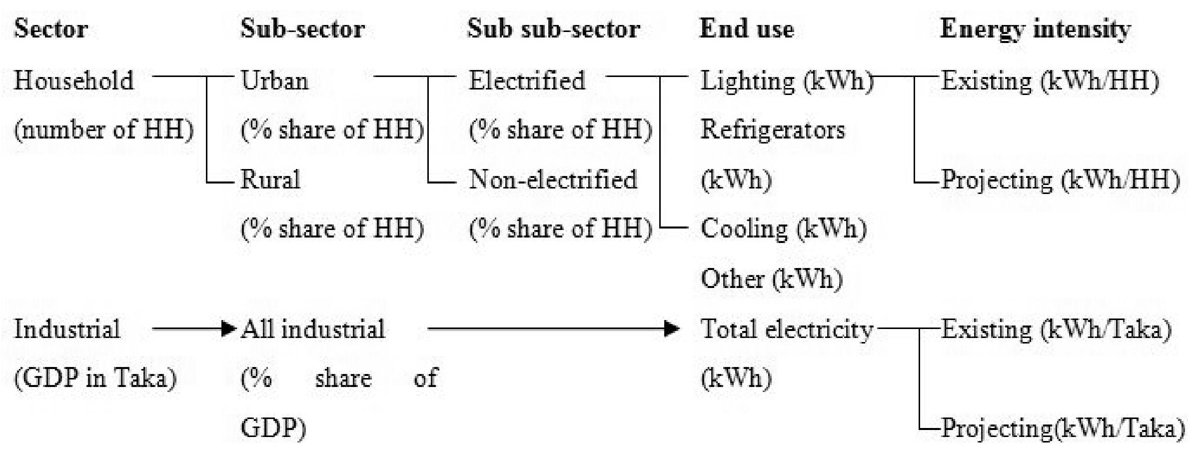

Figure 4.2: Tree structure applied in LEAP methodology (HH = household)

Several in-built modeling functions of LEAP were used for developing the scenarios. One of the most utilized functions is *Growth*, used for assessing the share and growth of electrical appliances. The change in the current (dependent) branch (electrical appliances) is related to the change in the named branch (income) raised to the power of the elasticity[4] (Kadian et al. 2007). This is equivalent to the following formula:

$$Current\ value\ (t) = \frac{Current\ value\ (t-1) \cdot Named\ value\ (t)}{Named\ branch\ value\ (t-1)} \tag{4.1}$$

The function *interp* was used to calculate a value in any given year by interpolation of a time series of year and value pairs. Each intermediate year value is calculated as:

[4] Elasticity is the ratio of the change in one variable with respect to change in another variable such as the percentage change in energy consumption to achieve one percent change in national GDP.

$$Value_{iy} = Valu_{ey} + \left[Value_{ey} - Value_{fy}\right]\left[\frac{Year_{iy} - Year_{fy}}{Year_{ey} - Year_{fy}}\right] \quad (4.2)$$

where *iy* is the intermediate period, the value of which is to be interpolated, *ey* is the end period used as the basis for interpolation and *fy* is the first period used as the basis for interpolation.

4.2.2 Scenario generation

GDP has been used as the best proxy to link electricity demand with economic activities in many developing countries. Various studies have focused on different countries and time frames, and have used different proxy variables for energy consumption and income. In the recent last years, numerous studies (Table 4.1) have been devoted to studying the causal relationship between economic growth and electricity consumption to confirm national electricity policies, as the direction of causality has significant policy implications for the government regarding the design and implementation of its electricity policy. The empirical results of these studies have been varied and sometime conflicting. The outcomes differ even on the direction of causality and it's long-term versus short-term impact on energy policies.

Table 4.1: Relationship between electricity consumption and GDP in developing countries

Study	Country	Variable used	Period	Relationship
Morimoto and Hope 2004	Sri Lanka	GDP and electricity production	1960-1998	Electricity ↔ Income
Aqeel and Butt 2001	Pakistan	GDP and energy consumption	1955-1996	Electricity → Income
Mozumder and Marathe 2007	Bangladesh	GDP and electricity consumption	1971-1999	Electricity → Income
Ghosh 2002	India	GDP and electricity consumption	1950-1997	Income → Electricity
Shiu and Lam 2004	China	GDP and electricity consumption	1971-2000	Electricity → Income
Chen et al. 2007	10 Asian countries	GDP and electricity consumption	1971-2001	Electricity ↔ Income

Mozumder and Marathe (2007) found unidirectional causality between GDP and electricity consumption in Bangladesh. Some reports also indicate that to reduce poverty to a moderate level, the required GDP growth is 7 %, and an electricity growth rate 1.5 times the GDP growth rate needs to be achieved (GSMP 2006; Jamaluddin 2008). It is recognized that the pace of power sector development has to be accelerated in order to achieve overall economic development of Bangladesh. To upgrade the socio-economic conditions and to alleviate poverty, the power sector has been prioritized by the government.

During the last 12 years, Bangladesh's economy has regained pace and GDP grew at a constant rate. Increased economic activity, reflected in the GDP growth, is the key driver behind the increase in the electricity demand. Table 4.2 shows the historical GDP value, GDP growth rate, net energy generation, per capita generation and per capita consumption (ADB 2006; BBS 2008; BER 2004&2008; BPDB 2006). Compound average annual GDP growth over the last 12 years (1994 - 2005) was 5.5 %. This compares with the average annual net energy generation growth rate of 8 % over the same period. It is imperative that Bangladesh maintains a strong GDP growth rate. Only through sustained growth will Bangladesh be able to achieve its target for poverty reduction and a general improvement in the quality of life for the country's people. Three GDP growth scenarios updated from PSMP (2005) and GSMP (2006) are assumed for the Bangladesh electricity demand analysis. In all scenarios, continued robust growth of Bangladesh's economy is assumed. It is assumed that as the economy grows, economic growth is more difficult to sustain. Therefore, the growth rates are higher in the early years than in the later years of the analysis period.

Table 4.2: GDP, electricity generation and consumption in Bangladesh 1994 - 2005

Year	GDP (Million Taka; 100 Taka = 1.569 USD)	GDP growth (%)	Net electricity generation (GWh)	Per capita electricity generation (kWh)	Per capita electricity consumption (kWh)
1994	1515139		9222.1	84.19	64.08
1995	1589762	4.93	10166.3	92.06	71.32
1996	1663240	4.62	10832.9	96.79	75.88
1997	1752847	5.39	11242.9	99.03	78.90
1998	1844478	5.23	12194.2	101.84	80.88
1999	1934291	4.87	13637.7	112.89	88.69
2000	2049276	5.94	14739.1	119.71	95.85
2001	2157353	5.27	16254.2	128.97	106.08
2002	2252609	4.42	17444.8	136.02	113.80
2003	2371006	5.26	18422.1	143.77	122.43
2004	2501813	5.52	20062.1	153.77	133.11
2005	2669740	5.96	21596.6	160.13	139.68

Low GDP growth scenario

The low GDP growth track is consistent with recent GDP growth trends and implies that the Bangladesh economy continues to grow the rate of the past 12 years. Under this scenario, the real GDP growth rate stabilized at 5.5 % in 2009 and continues at this level through to 2025, when it drops to 5.3 % and stays at this level until 2035.

Average GDP growth scenario

The average GDP growth track is consistent with Bangladesh's Poverty Reduction Strategy Paper (PRSP) and Millennium Development Goal (MDG). Under this scenario, the real GDP growth rate rises to 7 % by 2011, peaks at 8 % in 2016, drops to 6.5 % by 2026 and stays at this level until 2035.

High GDP growth scenario

The high GDP growth track is consistent with a highly optimistic level of economic and industrial development. The GDP growth rate increases rapidly to 7 % by 2009 and continues in an upward trend to a peak of 9 % in 2015 and 2016. From this peak point, GDP growth declines gradually to 8 % by 2035.

These three GDP growth scenarios and recent actual GDP growth trends will be used to forecast the demand for the Bangladesh electricity sector (Figure 4.3).

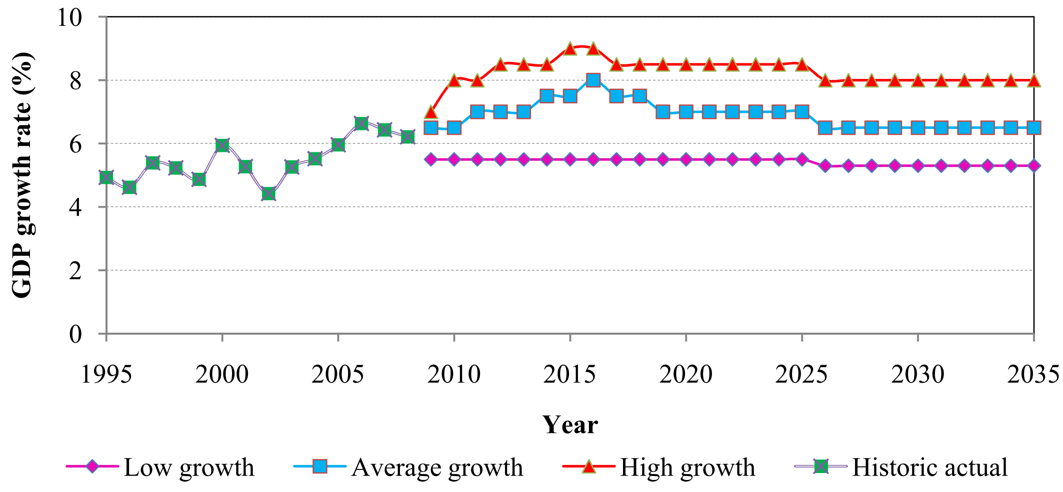

Figure 4.3: GDP growth scenarios

4.2.3 Projecting energy intensity and activities

Bangladesh is an agrarian country with a population of 137.4 million (2005). Only 22.9 % live in urban areas, while the remaining 77.1 % live in rural areas. An average household has around 5 members, and the total number of households in the country is 27.5 million. Population levels have been growing at a steady 1.5 % per year in recent years, down from 2.2 % in the 1980's and 1.8 % in the 1990's, indicating that population control initiatives have been relatively successful. It is assumed that the total population of the country will stabilize at 200 million (Islam and Huda 1999).

In 2005, most of the Bangladesh GDP was generated by the commercial sector, which accounted for 45.9 %, while the remaining 54.1 % came from agriculture (20.1 %), industry (19.1 %) and other (14.8 %) sectors (Table 4.3; BBS 2008; BER 2004, 2008; FFYP 1998). Other sectors include public administration and defense, education, health and social services, community, social and personal services. Although the commercial sector is large in GDP terms, Bangladesh remains heavily dependent on agriculture, which provides employment for over 50 % of the workforce (GSMP 2006). The contribution of agriculture to the national income is the second highest, but this has decreased. While in 1995 the agricultural contribution to the GDP at constant market prices was 30.3 %, it was 20.1 % in 2005.

Table 4.3: Sector GDP share (%) in Bangladesh 1995 - 2007

Sector/Year	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Industry	13.8	14.28	15.6	16.3	18.02	17.86	18.57	18.34	18.55	18.88	19.14	19.89	20.61
Agriculture	30.31	32.24	29.82	29	25.58	25.58	25.03	23.98	23.46	21.04	20.14	19.61	21.11
Commerce	40.89	38.98	39.58	40.2	41.08	41.48	41.44	42.69	43.08	45.22	45.9	45.78	43.61
Other	15	14.5	15	14.5	15.32	15.08	14.96	14.99	14.91	14.86	14.82	14.72	14.67

To forecast electricity consumption, electricity consumption data for the period 1994 - 2004 were analyzed (Table 4.4; BER 2008; BPDB 2005, 2006; PSMP 2005). The BPDB, Dhaka Electric Supply Authority (DESA) and Dhaka Electric Supply Company Limited (DESCO) mainly supply electricity to the urban areas while the Rural Electrification Board (REB) supplies the rural areas.

Industrial sector

The industrial sector is the largest consumer of electricity in Bangladesh. It consumes about 43 % of the total energy demand. The annual growth rate of this sector in the last 12 years was about 8 %. Besides use of electricity from public utilities, this sector uses electricity from captive power generation. The energy demand is expected to grow rapidly in the coming years.

The overall level of the industrial energy intensity per unit of industrial GDP was 0.012 kWh/Taka (100 Taka = 1.569 USD in 2005) in 1997 (Table 4.5). It grew to 0.014 kWh/Taka in 2005 with an average annual increase rate of 1.2 %. It is assumed that in the high GDP growth scenario (HG scenario), the energy intensity per GDP unit increases with a rate of 1.5 % to 0.018 kWh/Taka in 2020, and from 2020 onwards it decreases by a rate of 1 % and reaches 0.015 kWh/Taka in 2035 due to the expected greater diversity in the output of industrial goods and improvements in product quality and value. Industrial modernization, restructuring and increasing efficiency will lead to a significant improvement in the industrial sector energy intensity. For the initial years 2005 - 2015, the intensity increases because out-dated and low-efficiency technologies are widely used.

Table 4.4: Electricity consumption in Bangladesh 1994 - 2005 (total sales figures for each utility are the sum of the sales of each customer class, i.e., residential, agricultural, commercial and industrial)

Year	Utility	Energy sales by customer class (GWh)						Dist. loss (%)	Imported energy (GWh)	Trans loss (%)	Load shedd. (MW)
		Resid.	Agricul	Comm.	Indus.	Other	Total				
1994	BPDB	1181.3	98	315.5	1303.7	123.4	3021.9	30.7	4361.5	4.7	540
	DESA	889.2	13.4	199.7	1189.9	69.7	2292.2	32.9	3519.6		
	REB	245.2	157.3	43.1	317.6	1.9	765.1	15.6	906.1		
	Total	2315.7	268.7	558.3	2811.2	125.3	6079.2	30	8787.2		
1995	BPDB	1231.1	145	305.9	1402.7	134.4	3220.2	29.9	4596.3	4.1	537
	DESA	1079.1	15.8	202.5	1294.3	72.7	2664.4	31.9	3913.5		
	REB	322.9	273.3	57.5	394.3	2.1	1050.1	15.1	1237.3		
	Total	2633.1	434.1	565.9	3091.3	209.2	6934.7	28.9	9747.1		
1996	BPDB	1313.6	125.7	314.9	1468.7	139.7	3362.6	29.1	4742.1	4.2	545
	DESA	1238.6	15.5	200.7	1383.5	80.9	2919.2	31.5	4261.1		
	REB	415.6	242	68.9	441.4	4.3	1172.2	14.6	1372.2		
	Total	2967.8	383.2	584.5	3293.6	224.9	7454	28.2	10375.4		
1997	BPDB	1291.2	107.5	306.9	1519.9	135.4	3360.9	28.3	4686.2	4.2	674
	DESA	1455.5	10.1	206.4	1484.6	83.8	3240.4	29.8	4613.5		
	REB	462	208.1	72.7	472.9	4.6	1220.3	17.1	1472.5		
	Total	3208.7	325.7	586	3477.4	223.8	7821.6	27.4	10772.2		
1998	BPDB	1322.3	104.9	320.7	1602.8	133.7	3484.4	29.8	4965.3	4.4	711
	DESA	1641.3	8.4	202.7	1523.5	87	3462.9	30.4	4973.7		
	REB	586.5	191.5	87.9	564.3	4.8	1435	16.5	1718		
	Total	3550.1	304.8	611.3	3690.6	225.5	8382.3	28.1	11657		
1999	BPDB	1446.5	111.3	354.4	1667.3	146.4	3725.9	30.6	5365.5	4.7	774
	DESA	1722.9	4.4	195.8	1583.8	82.7	3589.6	30.8	5183.7		
	REB	793.2	312.1	118.5	759.9	5.4	1989.1	18.6	2442.7		
	Total	3962.6	427.8	668.7	4011	234.5	9304.6	28.4	12991.9		
2000	BPDB	1565.6	88.4	390.7	1835.8	160.5	4041	27.7	5591.6	4.9	536
	DESA	1471.4	1.1	171.1	1886.9	51.7	3582.2	31.7	5247.7		
	REB	1005.2	262.2	149.5	1034.6	8.2	2459.7	22.5	3172.4		
	Total	4042.2	351.7	711.3	4757.3	220.4	10082	28	14011.7		
2001	BPDB	1725	111	440.3	1968.8	174.8	4419.9	26.1	5981.9	4.2	663
	DESA	1639.3	0.9	167	2002.3	48.9	3858.4	32.5	5718.7		
	REB	1230.5	370.9	180.6	1340.3	8.3	3130.6	19	3864.2		
	Total	4594.8	482.8	787.9	5311.4	232	11408	26.7	15564.8		
2002	BPDB	1891.7	96.2	473.7	2090.5	184.2	4736.3	24.5	6273.4	3.8	367
	DESA	1691.5	0.7	159.5	1419.4	51.5	3322.6	36.6	5380.5		
	DESC	267.9	0	23.8	185.8	16.1	493.6	25.2	660.3		
	REB	1659.9	357.2	219.4	1648.7	9.8	3895	17.2	4466.2		
	Total	5511	454.1	876.4	5344.4	261.6	12447	25.3	16780.4		
2003	BPDB	1993.7	75.3	497.4	2078.4	192.9	4837.7	22.4	6230.5	3.8	468
	DESA	1657.6	0.3	211.9	1547	52.7	3469.5	33	5184.6		
	DESC	348	0	41	256	31	676	21.5	861.4		
	REB	2037	399	268	2173	11	4888	14.1	5447.5		
	Total	6036.3	474.6	1018.3	6054.4	287.6	13871	21.7	17724		
2004	BPDB	2066.7	78.8	504.7	2086.8	204.3	4941.3	21.3	6281	3.5	694
	DESA	1379	0.2	222	1529	48	3178.2	34.5	4854		
	DESC	678	0	104	597	29	1408	19.1	1740		
	REB	2475	527	320	2469	14	5805	13.7	6486		
	Total	6598.7	606	1150.7	6681.8	295.3	15332	20.8	19361		
2005	BPDB	2016	76	498	1557	235	4382	20	5258.4	3.5	770
	DESA	1601	0.2	254	1979	105	3939.2	21.94	4803		
	DESC	746	0	123	631	36	1536	16.64	1791.6		
	REB	3186	793	489	2917	15	7400	13.7	8414		
	WZPD	135	73	22	153	5	388	15	446		
	Total	7684	942.2	1386	7237	396	17645	17.45	20714		

The GDP share in this sector was only 13.8 % in 1995, while it grew to 20.16 % in 2007 with an annual average growth rate of 3.8 %. It is projected that the GDP share in this sector will reach 46 % in the HG scenario (annual increase of 3 %) and 31 % (annual increase of 1.6 %) in the low growth scenario (LG scenario) by the year 2035. In average growth scenario (AG scenario), the industrial share of GDP is increased annually by 2.3 % in the analysis period (2005 - 2035).

Table 4.5: Industrial sector GDP share and energy intensity in Bangladesh by scenario (2005 – 2035)

Scenario	Categor	Unit	2005	2010	2015	2020	2025	2030	2035
Low growth			19	21	23	25	27	29	31
Average growth	GDP share	%	19	22.16	25.33	28.5	31.66	34.83	38
High growth			19	23.5	28	32.5	37	41.5	46
Low growth			0.014	0.015	0.015	0.016	0.015	0.014	0.014
Average growth	Intensity	kWh/Taka	0.014	0.015	0.016	0.016	0.015	0.015	0.014
High growth			0.014	0.015	0.016	0.018	0.017	0.016	0.015

Commercial sector

Forecasts on energy demand in the commercial sector are made in terms of energy intensity (kWh/million Taka). The consumption in this sector is relatively low in comparison to that in the industrial sector, i.e., only 7 to 8 % of the total electricity consumption. In contrast, this sector has the largest GDP share, i.e., 46 % (2005). Consumption is expected to increase rapidly over the next decades. The recent trend shows an annual increase in energy intensity by 3.5 %. The AG scenario considers an average annual growth rate of 2 % from the 2005 value of 1128 kWh/million Taka to 2044 kWh/million Taka in 2035. For the HG scenario, energy intensity increases sharply by 4 % annually to 2000 kWh/million Taka in 2020 and remains constant due to improvements in the efficiency of end-use appliances in the later period (Table 4.6). The GDP share decreases slightly; its share is replaced by that of the industrial sector.

Table 4.6: Commercial sector GDP share and energy intensity projections by scenario

Scenario	Category	Unit	2005	2010	2015	2020	2025	2030	2035
Low growth			46	43.74	41.6	39.6	37.6	35.77	34
Average growth	GDP share	%	46	43.33	41.67	39.5	37.33	35.17	33
High growth			46	43.67	41.33	39	36.67	34.33	32
Low growth			1128	1240	1352	1464	1576	1688	1800
Average growth	Intensity	kWh/million Taka	1128	1246	1376	1519	1677	1851	2044
High growth			1128	1419	1709	2000	2000	2000	2000

Agriculture and other sectors

Agriculture is a seasonal business and therefore the demand for energy fluctuates throughout the year. Diesel oil and electricity are two major sources of energy in this sector. The total demand of electricity for agriculture has increased over the years, but the relative percentage of consumption has changed little in the past years. Consumption in this sector was only 434 GWh in 1995 but had increased to 942 GWh by 2005. The share of electricity consumption was 5.33 % in 2005. The total number of irrigation-pump connections was around 43,000 in 1995 and reached around 162,000 by 2005 (REB 2006). Due to shortage of power, the government has recently stopped the extension of new electricity connections for the rural residential sector, but it is continuing the connections to irrigation pumps.

The agricultural sector is the largest sector in the Bangladesh economy. Its contribution to the national income is the second highest. However, in 2005 the share of the GDP at constant market prices had dropped to 20 % from around 30 % in 1995. The future electricity demand for this sector is also projected based on energy intensity (kWh/million Taka), which has increased by 5 % in recent years (Table 4.7).

Electricity for other sectors consists of street lighting, water pumps, mosques, etc., and plays only a minor role in the overall power consumption. Its share of total electricity consumption in 2005 was about 2 %. The GDP share has hardly changed in recent years, although a slight decrease has been observed.

Table 4.7: Agricultural sector GDP share (%) and energy intensity by scenario

Scenario	Category	Unit	2005	2010	2015	2020	2025	2030	2035
Low growth			20	20	20	20	20	20	20
Average growth	GDP share	%	20	19.1	18.33	17.5	16.66	15.83	15
High			20	18.66	17.33	16	14.66	13.33	12
Low growth			1764	2045	2371	2748	3186	3694	4282
Average growth	Intensity	kWh/million Taka	1764	1996	2258	2555	2891	3270	3700
High			1764	1948	2150	2374	2621	2894	3195

Residential sector

Consumption of electricity and commercial energy as a whole is increasing in the residential sector. Population increase and access to electricity coupled with higher income and increased numbers of electrified households are some of the reasons for this change. Access to electricity of the population was only 15 % in 1996, while it grew to 38 % by 2005 (BPSDB 2006). Between 1995 and 2005, electricity consumption in this sector grew at an annual rate of 11.2 %. In 1995, the demand for electricity was 2633 GWh and increased to 7684 GWh by 2005.

The goal of the Bangladesh government of electricity for all by the year 2020 is ambitious. As REB forecasts that only 84 % of the population in rural areas will have an electricity supply by 2020, the percentage of connected urban areas is expected to be higher. In the residential sector scenario, it is assumed that 84 % of the rural and 100 % of the urban households will be connected to electricity by 2020 (Table 4.8).

Table 4.8: Population, electrification and urbanization level by scenario

Scenario	Residential Sector	Population Level (million)		Electrification Level (%)		Urbanization (%)	
		2020	2035	2020	2035	2020	2035
Low growth		54.95	80	92	100	31.4	40
Average growth	Urban	57.56	90	95	100	33.9	45
High growth		61.4	100	100	100	36.4	50
Low growth		120.05	120	59.6	84	31.4	40
Average growth	Rural	117.43	110	68.8	84	33.9	45
High growth		113.59	100	84	84	36.4	50

Urban and rural residential sectors are projected separately in order to account for their significantly different energy service demand, and to allow for the trend of urbanization to be included in the LEAP modeling. The categories of electricity use considered in both urban and rural residential sectors are lighting, refrigerators, cooling and other electrical appliances, which are projected independently (Table 4.9). With respect to lighting and other electric appliances, it is assumed that 100 % of the households use these. In the rural residential sector, 69 % of the households are equipped with electric fans (USAID 2002) and 21 % with refrigerators (Khan 2006).

Lighting

The lighting service demand in the urban and rural electrified residential sectors is satisfied solely by electricity using either incandescent or mercury vapor lamps. Lighting consumption alone is around 40 % of the total consumption in the residential sector in urban areas (Islam 2003) and 48.2 % in rural areas (Khan 2006). In 2005, the urban electricity demand for lighting was 358 kWh per electrified household and 315 kWh in rural households. The lighting demand is projected to grow at a constant rate of 1.3 % per year to reach 430 kWh in 2020 when the demand will be saturated. From 2020 onwards, this demand is assumed to decrease by 1 % per year to reach a level of 375 kWh in 2035 for the HG scenario due to the introduction of compact fluorescent lamps (CFL).

The increase rate is relatively low considering the GDP growth rate. It is kept in mind that efficient lamps will decrease the total lighting demand, and the gradually decreasing demand growth rate reflects the saturation of the household lighting demand of a part of the households in the urban areas. The rural residential lighting demand is projected to grow to the level of the current urban demand by 2020, 2025 and 2035 in the HG, AG and LG scenarios, respectively (Table 4.10).

Table 4.9: Projected household use of refrigerators and cooling (%) by scenario

Scenario	Residential sector	Category	2005	2020	2035
Low growth			40	52.5	65
Average growth	Urban	Refrigerator	40	60	80
High growth			40	65	90
Low growth			21	33	45
Average growth	Rural	Refrigerator	21	38	55
High growth			21	45.5	70
Low growth			75	77.5	80
Average growth	Urban	Cooling	75	85	95
High growth			75	87.5	100
Low growth			69	74.5	80
Average growth	Rural	Cooling	69	79.5	90
High growth			69	84.5	100

Cooling

The tropical climate in Bangladesh requires cooling, which is satisfied mainly by cooling fans. Only few high-income urban households have air-conditioning systems. In 2005, an average 323 kWh was consumed for cooling per urban household and 187 kWh per rural household. The electricity consumption is assumed to grow at an average annual rate of 1.5 % to reach the level of 403 kWh per household by the year 2020 in the urban residential sector in the HG scenario. From 2020 onwards, the consumption rate per household increases with a lower rate of 1 % per year to reach 468 kWh by the year 2035. In the AG scenario, the peak level of consumption of 403 kWh is reached by 2025 and increases by 1 % per year till 2035. In the LG scenario, the peak level of 403 kWh is reached by the year 2035.

In rural households, the electricity consumption for cooling increases to the present consumption level of urban household by the year 2020 in the HG scenario. It is projected to continue to grow to 350 kWh by the year 2035. The final consumption levels in this category are 340 kWh and 322 kWh in the AG and LG scenario, respectively (Table 4.10).

Refrigeration

Electricity for refrigeration also represents an important fraction of the urban residential load (about 22 %; Islam 2003). In 2005, 40 % of the urban households were equipped with refrigerators, while this was 21 % in the rural households (Table 4.9). In the HG scenario, it is assumed that 90 % of the urban and 70 % of the rural households will be equipped with refrigerators by the year 2035. By 2035, in the AG scenario 80 % urban and 55 % rural households will have refrigerators and in the LG scenario 65 % urban and 45 % rural households.

The electricity consumption for refrigeration per household in the urban residential sector was 492 kWh in 2005. In rural areas, it was only about 318 kWh due to massive electricity cuts there. The demand is expected to grow at the rate of 0.7 % in the HG scenario until 2020 and then it remains constant for urban households. It is projected that in 2020, rural households will have the same consumption levels as urban households in 2005. After 2005 the demand increases by 1 % per year in the HG scenario (Table 4.10).

Table 4.10: Energy intensity (kWh per electrified household) of residential sector by GDP growth scenario

Scenario	Residential sector	Category	2005	2020	2035
Low growth			358.4	380	380
Average growth	Urban	Lighting	358.4	400	375
High growth			358.4	430	375
Low growth			315.2	336.6	358
Average growth	Rural	Lighting	315.2	348	358
High growth			315.2	358.4	340.5
Low growth			323	363	403
Average growth	Urban	Cooling	323	391	423
High growth			323	403	468
Low growth			187	254	322
Average growth	Rural	Cooling	187	289	340
High growth			187	322	350
Low growth			493	532	571
Average growth	Urban	Refrigerator	493	551	571
High growth			493	571	571
Low growth			318	405.2	493
Average growth	Rural	Refrigerator	318	448.4	520
High growth			318	493	571
Low growth			99	195	247
Average growth	Urban	Other appliances	99	229	305
High growth			99	265	371
Low growth			30	59	75
Average growth	Rural		30	70	93
High growth			30	81	112

Other electrical appliances

In addition to refrigerators, households use miscellaneous electrical appliances namely irons, televisions, computers, etc. Consumption depends on how well equipped the household is with such appliances and also on the technical characteristics of the appliances.

The electricity demand for the other electrical appliances in the urban residential sector in 2005 was 99 kWh per household. The demand is projected to grow in proportion to the GDP growth rate according to an elasticity of 1.0 in the initial period 2005 to 2015 decreasing to 0.5 in the future period 2015 to 2025 and 0.2 in the final analysis period 2025 to 2035 (Table 4.10).

In 2005, around 47 % of the rural households had a television (USAID 2002). This percentage is expected to increase to 90 % by 2035. Consumption of other electrical appliances without televisions was only 30 kWh per rural household in 2005. This is expected to increase significantly over the next 35 years, as the improving living standard will lead to a growing demand for electrical appliances. Consumption in the rural residential sector is projected to grow at a rate proportional to the growth of GDP, according to the elasticity of 1.2 initially (2005 - 2015), which is then reduced to 0.8 (2015 - 2025) and finally 0.3 (2025 - 2035) (Table 4.10). The main reasons for such strong growth, especially in the near future are:

1) Introduction of the market economy clearly improves living conditions and offers the households a broad range of goods. The number of families who can buy electrical appliances increases accordingly.
2) The urbanization process, which is increasing more than 2 % per year.

4.3 Final electricity demand

Total electricity consumption was 17.7 TWh in 2005 and is projected to increase 7.5 times to 132 TWh by 2035 in the LG scenario (Figure 4.4). In the AG and HG scenarios, the demand in 2035 shows an increase that is about 11 and 16 times the base-year value, respectively. In the HG scenario, due to the higher share of the industrial sector GDP, the industrial demand increases from 7.2 TWh in 2005 to 185.4 TWh in 2035 with an annual average growth of 11.4 %. In the AG and LG scenarios, the industrial sector demand is projected to increase at an annual average growth rate of 9 % and 7 %, respectively.

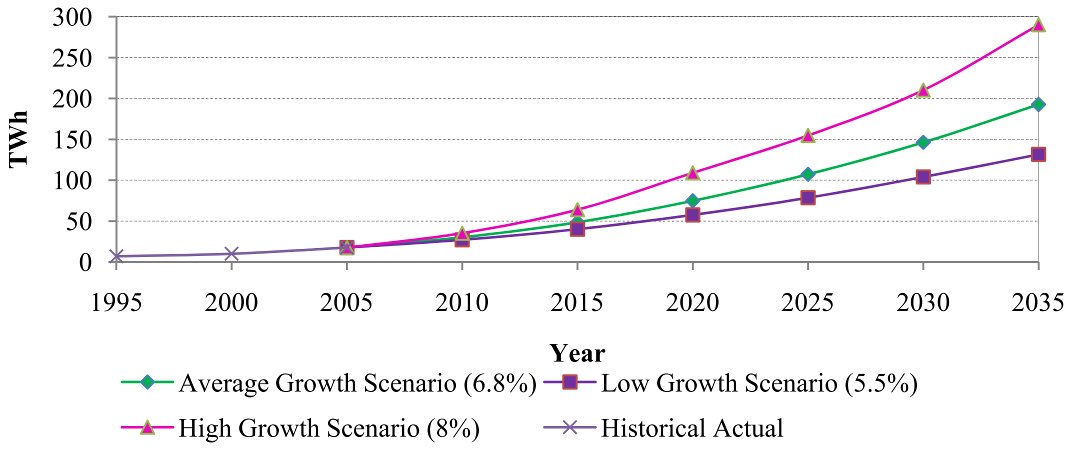

Figure 4.4: Historic and projected total electricity demand

In 2005, the share of the residential, agricultural, commercial and industrial sectors of the total electricity consumption was 43.6 %, 5.3 %, 7.9 % and 41%, respectively. Other sector consumption was 2.3 % in this year. By 2035, in the HG scenario, the residential and agricultural sectors consume 25.8 % and 3.6 %, respectively, the while commercial and industrial sectors consume 5.9 % and 63.9 %, respectively. In the LG scenario, in 2035 the share is almost the same as in 2005.

It is worth mentioning here that the actual GDP growth rate in Bangladesh lies between a low and a high rate. In the MARKAL Bangladesh model developed for this study, average growth rates are used. For illustrative purpose, final electricity demand projections for each sector in the average GDP growth scenario are discussed.

The consumption of electricity in the residential sector increases significantly, as almost the entire country is connected to the electricity network. In the AG scenario, the total residential sector consumption was 7.7 TWh in 2005 and is projected to increase about 8-fold to 64.5 TWh (Table 4.11 and Figure 4.5) in 2035 with an annual average growth rate of 7.3 %. In the urban residential sector, the consumption was 4.5 TWh in 2005 and increases about 8-fold by 2035. Similarly, in the rural residential sector, it increases about 9.4 times by 2035, as the access to electricity increases sharply from 23 % in 2005 to 84 % in 2025.

In the industrial sector, electricity consumption is projected to increase about 14-fold by 2035 in AG scenario. The increases in electricity demand in this sector are due to the economic transition from the agricultural to the industrial sector. The agricultural sector demand also increases significantly over the analysis period. In 2005, total consumption was only 0.9 TWh and increases about 11.4 times by 2035. The sharp increases in this sector are due the use of electric motors instead of diesel engines for the irrigation pumps as a result of the ongoing installation of additional pumps across the country to achieve self-sufficiency in food production.

In 2035, the residential and agricultural sectors consume 33.5 % and 5.5 %, respectively, while the industrial and commercial sectors consume 52.7 % and 6.7 %, respectively under AG scenario (Figure 4.6).

Table 4.11: Final electricity demand in TWh in Bangladesh (2005 - 2035)

Category	2005	2010	2015	2020	2025	2030	2035
Urban residential	4.51	7.40	11.49	16.99	23.88	30.29	34.61
Rural residential	3.19	6.56	10.93	16.19	22.16	27.03	29.85
Agriculture	0.94	1.42	2.13	3.20	4.79	7.16	10.67
Commerce	1.39	2.03	2.95	4.30	6.23	9.00	12.96
Industry	7.24	12.26	20.31	33.07	48.64	70.65	101.50
Other	0.40	0.56	0.79	01.11	1,56	2.19	3.09
Total	17.67	30.23	48.6	74.86	107.3	146.3	192.7

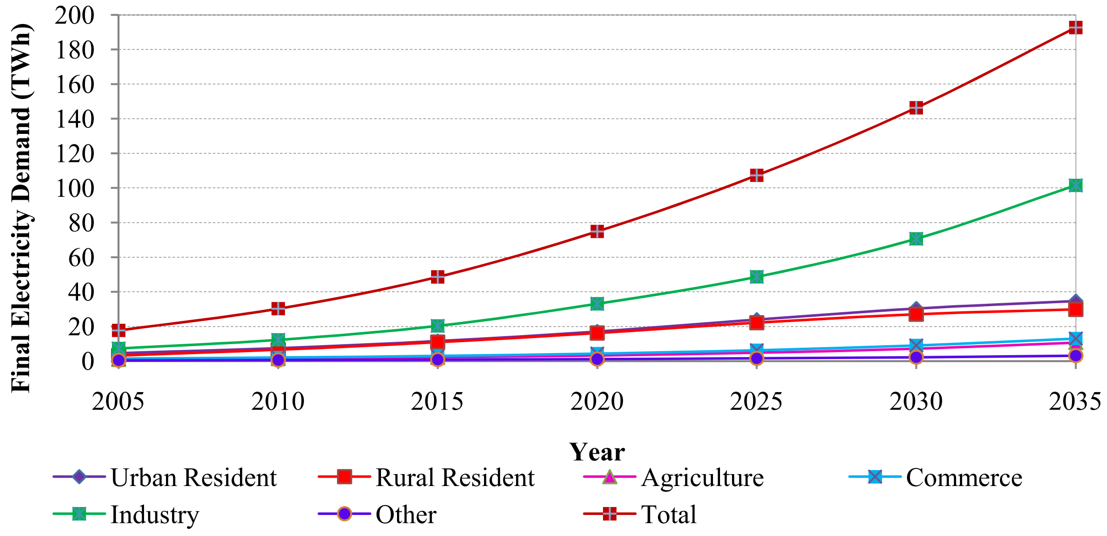

Figure 4.5: Final electricity demand under the average GDP growth scenario

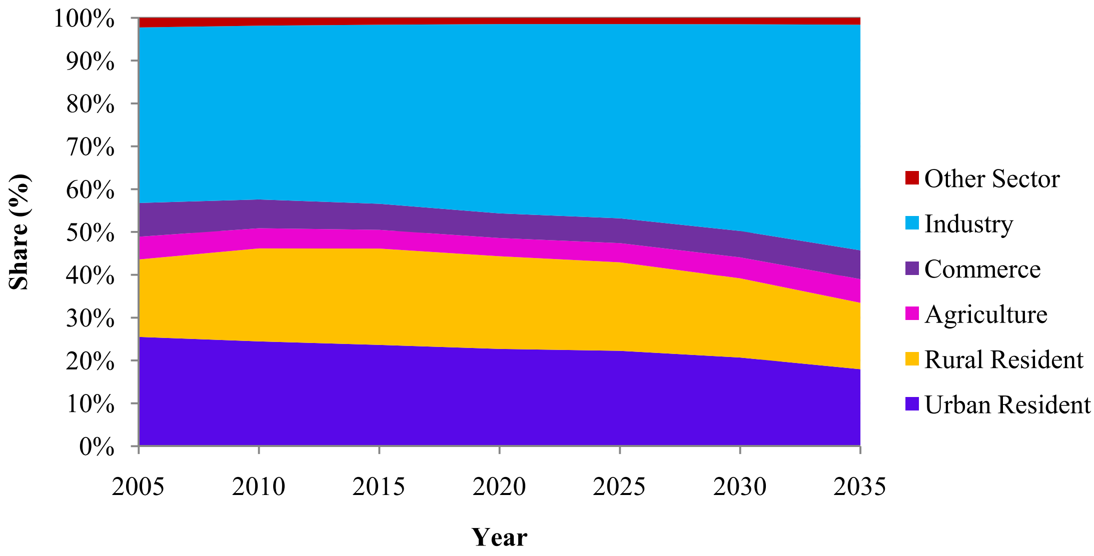

Figure 4.6: Sectoral share of electricity demand under the average GDP growth scenario

In order to provide a context for this demand forecast, all study scenarios are compared with the forecasts developed for the update power sector master plan (PSMP) using regression analysis (Figure 4.7). The PSMP's projection was in net generation up to 2025 and this study considers transmission and distribution losses of 20 % in the initial periods (2005 - 2015) and 15 % in the later periods (2015 - 2035) to obtain net generation of electricity (PSMP 2005). The comparison shows that the demand forecasts in this study are lower than PSMP's forecast. The reason for this is that the present study takes into account the demand by sectors while it analyzes the residential sector by category. Also, there are many other activities, events and trends that impact on the demand for electricity, i.e., increase in electrification level, use of energy-intensive goods, increased use of energy-efficient devices based on GDP growth trends.

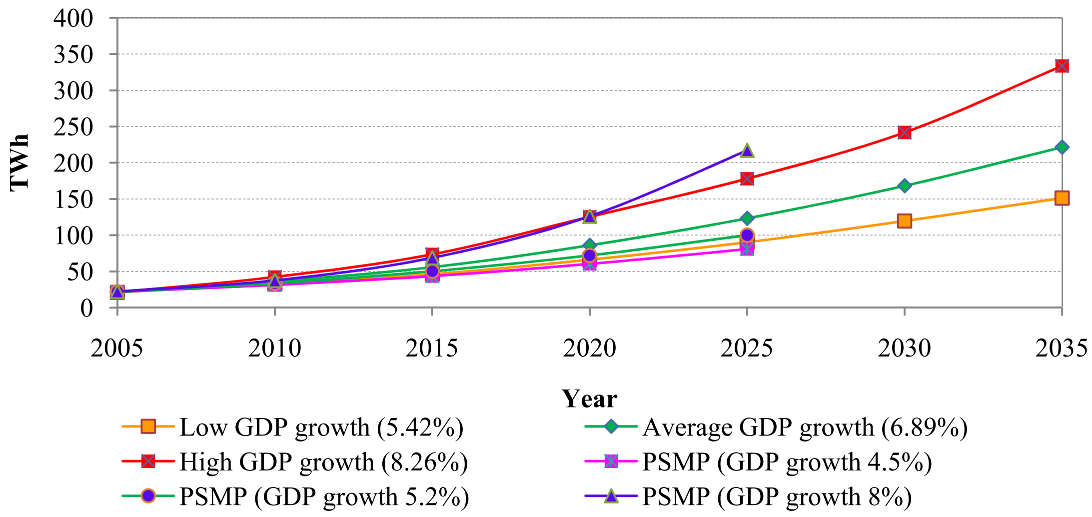

Figure 4.7: Comparison demand forecast between the study and the power sector master plan (PSMP)

The projected per capita electricity demand for Bangladesh over the next 30 years is compared with other developing countries (WB 2007) what they had been able to achieve in the past years (1976 - 2006) (Figure 4.8). The future years Bangladesh energy sector development follows almost the past years development of China, Thailand and Philippines. This is reasonable considering Bangladesh's economic structure and the lower per capita electricity base value compared to other developing countries.

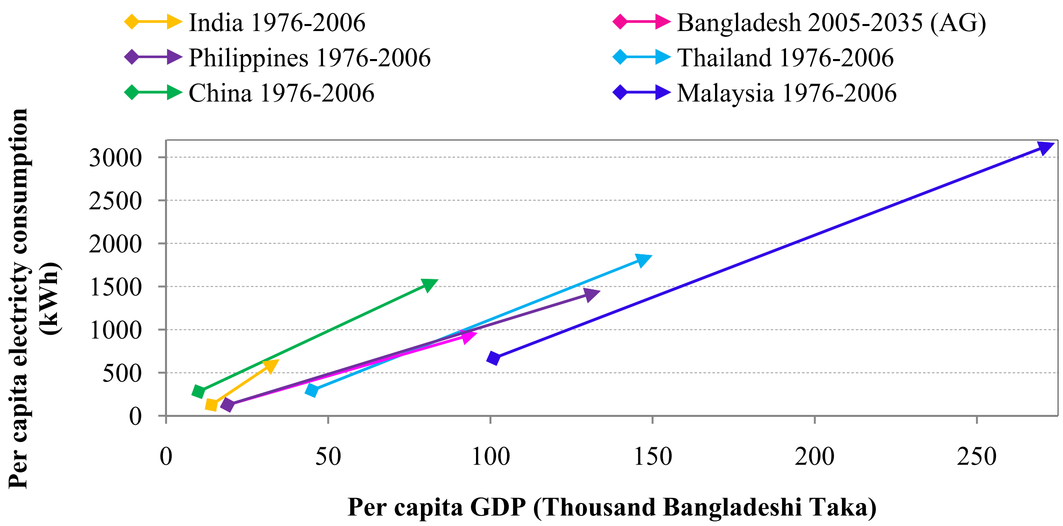

Figure 4.8: Projected per capita electricity consumption in Bangladesh (2005 - 2035) and historical data of selected developing countries

5 DEVELOPMENT OF THE MARKAL-BANGLADESH MODEL

The exogenous parameters of power generation used for the establishment of the MARKAL-Bangladesh model can be grouped in three broad categories: power or energy demand, availability of energy resources, and conversion technologies. Issues like market price of power, fuel prices, etc. although individually important, are linked in this study with any one or with a combination of the above categories. In the following sections, a comprehensive view of power generation, including development of a perspective view of the Bangladesh energy sector with special focus on power generation, is presented. The renewable energy technologies were discussed previously (Chapter 3). Modeling with MARKAL requires establishment of relationships between technologies, activities and energy flows from the primary energy stage up to the end-use through intermediate stages such as transportation and conversion. For this study, the Bangladesh power sector is taken as the reference energy system.

For the purpose of this study, i.e., to select the least-cost technologies for power generation, the MARKAL-Bangladesh model was developed in this chapter. A major part of the work was to develop input parameter values. In MARKAL, the reference energy system is the first step towards building a MARKAL-Bangladesh model of the Bangladesh power sector. The reference energy system represents the activities and technologies of an energy system, depicting energy demands, energy conversion technologies, fuel mixes, and the resources required to satisfy the energy demand (Mathur et al. 2003). Three basic sets of input information are required for each time step over the entire period of the analysis: 1) energy demands, 2) potential supply and cost of primary energy resources and 3) cost and performance characteristics of technologies potentially available for use in the energy system.

5.1 Energy service demand

In 1994, the total electrical energy demand was 9.6 TWh (PSMP 2005) and by 2005 had increased to 17.6 TWh. Based on the projections of GSMP (2006) and PSMP (2005), this energy demand will increase to 102.4 TWh and 100.1 TWh, respectively, in 2025. The LEAP tool was used to form demand scenarios according to the trend of GDP growth rates of 5.5 %, 6.8 % and 8 %, and to the nature of the energy sector itself, taking into consideration broader factors, e.g., population, households, urbanization and other influencing factors for the time span 2005 to 2035 (Chapter 4). The demand based on the average GDP growth rate of 6.8 % is considered for the MARKAL-Bangladesh model (Table 5.1).

Table 5.1: Final electricity demand in Bangladesh in TWh (2005 – 2035)

Category	2005	2010	2015	2020	2025	2030	2035
Urban residential	4.51	7.40	11.49	16.99	23.88	30.29	34.61
Rural residential	3.19	6.56	10.93	16.19	22.16	27.03	29.85
Agriculture	0.94	1.42	2.13	3.20	4.79	7.16	10.67
Commerce	1.39	2.03	2.95	4.30	6.23	9.00	12.96
Industry	7.24	12.26	20.31	33.07	48.64	70.65	101.50
Other	0.40	0.56	0.79	01.11	1,56	2.19	3.09
Total	17.67	30.23	48.6	74.86	107.3	146.3	192.7

5.2 Energy supply

5.2.1 Electricity supply

Installed capacity

Total installed power generation capacity in the country was 2908 MW in 1996 and had increased to 5245 MW by 2006 (Figure 5.1). Power generation in the country is almost entirely dependent on fossil fuels, mainly natural gas, which accounted for 81.4 % of the total installed capacity in 2006. Diesel, furnace oil (FO), coal and hydro generation capacity in the same year were 4.1 %, 5.3 %, 4.8 % and 4.4 %, respectively.

The power generation capacity increased at a rate of 18.8 % per year during the 1980s. The 1990s showed a decline in the growth rate of 5.3 % per year. The power generation capacity had increased annually by 5.9 % between 2000 and 2006.

Electricity generation

The increase in electricity generation in Bangladesh in general corresponded to the trend in installed capacity expansion. Net electricity generation was about 10.2 TWh in 1995 and had reached 23.7 TWh by 2006 (Figure 5.2). During the 1980s, electricity generation increased at an annual growth rate of 18.6 %, in the 1990s at a rate of 8.7 % and between 2000 and 2006 at a rate of 7.5 %.

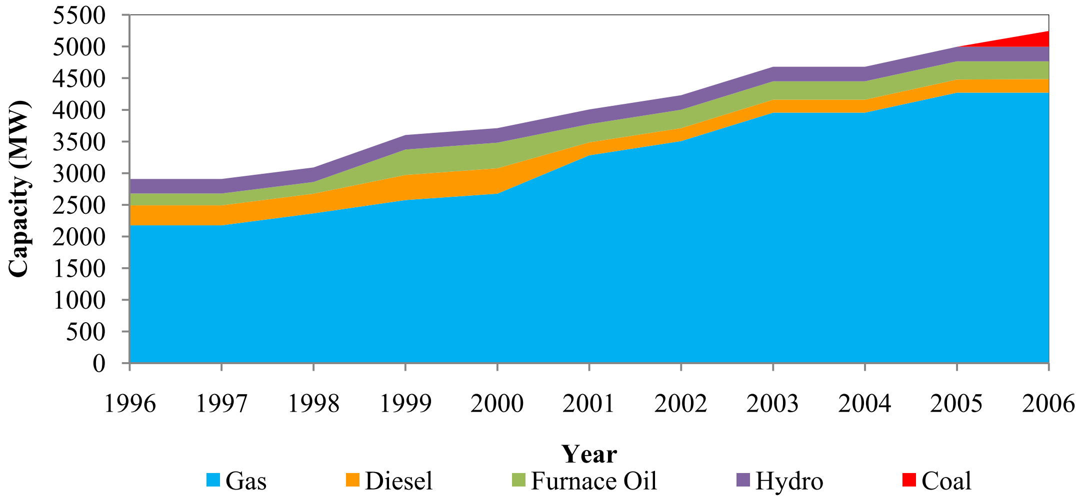

Figure 5.1: Power generation capacity from various technologies (BPDB 2000, 2002, 2006)

Transmission and distribution loss

The transmission and distribution (T&D) loss amounted to more than 20 % of the available power between 1995 and 2006 (Figure 5.2). Transmission losses dropped to 3.5 % in 2005 and peaked at 4.9 % in 2000. Distribution losses decreased from 28.9 % in 1995 to 17.3 % in 2006. The T&D losses were 21 % of the generated electricity in 2005.

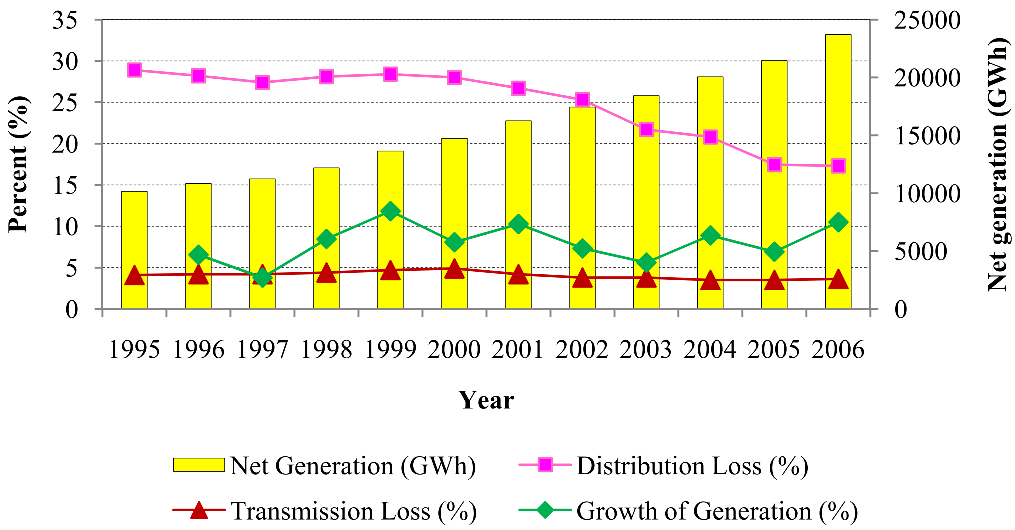

Figure 5.2: Power generation and transmission and distribution losses in Bangladesh (BPDB 2006; BPSDB 2006; PSMP 2005)

5.2.2 Primary energy resources and constraints

Primary energy requirement for power generation is met through conventional and non-conventional sources of energy. The term primary energy refers to the naturally available form of energy that may be in the form of coal, oil, gas or renewable energy such as solar irradiation, wind, hydropower and biomass.. Modeling of MARKAL requires that the costs of all primary energy resources (either that are extracted or imported, conventional or renewable) be defined along with their availability constraints. In the following, details of conventional energy resources and their availability for this study together with the projected costs and annual maximum production limits for conventional and renewable energy sources (Table 5.2 and Table 5.3) are presented.

Coal

Bangladesh has at least 1250 million tons of proven recoverable resources of coal and estimated reserves of about 2083 million tons (Imam 2005). Since the demand of coal is increasing in the country, total domestic coal production is mostly consumed internally and the coal price is, therefore, independent of the international market. In 2005, the average cost of coal in Bangladesh was 119.96 Taka/GJ (100 Taka = 1.569 USD) based on a calorific value of coal of 24 GJ/ton (BCP 2005; PSMP 2005). In this study, it is assumed that the cost of coal will increase at a constant rate of 2.5 % per year to reach 252 Taka/GJ in 2035 (Table 5.2). This increase accounts for higher mining costs due to the expected increase in future mine depths. Coal production in 2005 was 0.5 million tons, and the projected production capacity is 15 million tons in 2015 and from 2020 onwards 30 million tons (BCP 2005). In 2005, the average cost of imported coal in Bangladesh was 144.075 Taka/GJ (PSMP 2005). It is projected that this will increase at a constant rate of 4.6 % per year to reach 555 Taka/GJ in 2035 due to high transmission cost. A limit on imported coal is not considered here, but one scenario involves limitation of coal imports.

In mined coal, the average sulfur content is 0.57 % and carbon 46.2 % (Imam 2005). These values form the basis of the calculated emission coefficients used in this study. The IPCC database is used for the CO_2 emission of imported coal (IPCC 1996a).

Table 5.2: Projected production bounds and cost of conventional energy resources in Bangladesh (all costs are in 2005 Bangladeshi Taka where 100 Taka = 1.569 USD)

	2005	2010	2015	2020	2025	2030	2035
Extraction of natural gas							
Upper bound (PJ)	8000[5]						
Cost (million Taka/PJ)	66.67	83.48	104.53	130.88	163.89	205.22	256.96
Transmission cost (million Taka/PJ)	8.17	9.02	9.96	11	12.14	13.41	14.80
Extraction of coal							
Upper bound (million ton)	0.5	7.6	14	30	30	30	30
Upper bound (PJ)	12.27	186.2	343	735	735	735	735
Cost (million Taka/PJ)	120	135.76	153.61	173.79	196.63	222.47	251.70
Imported oil							
Diesel (million Taka/PJ)	607.20	760.30	952.02	1192.08	1492.67	1869.06	2340.35
Furnace oil (million Taka/PJ)	380	475.81	595.79	746.03	934.15	1169.70	1464.65
Imported hard coal							
Cost (million Taka/PJ)	144.07	180.4	225.89	282.85	354.17	443.48	555.31

Natural gas

Bangladesh has approximately 382.5 billion m^3 proven natural gas reserves and estimated probable gas reserves of about 810 billion m^3 (Petrobangla 2008). In 2005, domestic natural gas production was 13.78 billion m^3, and power sector consumption alone was 7.1 billion m^3 (51 %). In 1995, the natural gas consumption was 3 billion m^3 (Figure 5.3) At the current rate of increase in consumption (around 10 % annually), the national proven reserve of natural gas may not last more than 15 - 20 years (Bhuiyan et al. 2000; Hossain and Badr 2007).

In this study, the constraint is total gas availability for power generation based on the proven reserve (51 % of 382.5 billion m^3). Furthermore, a transmission loss of gas of 6.5 % and transmission cost of 0.3 Taka/m^3 are considered (Petrobangla 2008). Gas is highly subsidized in the power sector, where prices are lower than in other sectors. In 2005, natural gas in this sector was 2.6 Taka/m^3 or 66.7 Taka/GJ (Petrobangla 2008). It is projected to increase by a historical rate of 4.6 % per year to 2035 (Petrobangla 2008). Imported gas is not considered in this analysis. Due to

[5] Cumulative total gas resource for power generation

different carbon content percentages in different gas fields in Bangladesh, the IPCC (1996a) emission factor is used in the model.

Table 5.3: Projected production bounds and cost of renewable energy resources in Bangladesh (all costs are in 2005 Bangladeshi Taka where 100 Taka = 1.569 USD)

	2005	2010	2015	2020	2025	2030	2035
Extraction of rice husks							
Upper bound (PJ)	179.17	193.01	202.86	202.86	202.86	202.86	202.86
Cost (million Taka/PJ)	102	118.24	137.07	158.91	184.22	213.56	247.58
Power capacity (MW)	0	10	50	100	100	100	100
Extraction of bagasse							
Upper bound (PJ)	18.31	19.71	20.72	20.72	20.72	20.72	20.72
Cost (million Taka/PJ)	11	14	17.91	22.86	29.12	37.24	47.54
Power capacity (MW)	38	50	100	200	200	200	200
Extraction of MSW							
Upper bound (PJ)	21.46	23.89	26.38	28.41	30.61	30.61	30.61
Power capacity (MW)	0	0	20	50	80	100	200
Extraction of poultry droppings							
Upper bound (PJ)	49.28	54.40	60.06	64.70	69.67	69.67	69.67
Power capacity (MW)	0	10	20	100	100	100	100
Hydro							
Power capacity upper (MW)	230	230	330	550	550	550	550
Wind							
Power capacity upper (MW)	0	20	4614	4614	4614	4614	4614
Solar							
Power capacity (MW)[6]	0	20	50174	50174	50174	50174	50174

Oil

Only around 203 million liters of furnace oil (FO) and 152 million liters of diesel and kerosene were used to generate electricity in 2006 (BPDB 2006), which was about 13 % of the total imported oil products in the country (BER 2008). Proven oil reserves are estimated to be only about 8 million tons equivalent and Bangladesh needs to meets its oil demands through imports (Uddin 2006). Imported refined oil products (diesel,

[6] The installed capacity of solar PV is allowed to grow at a maximum rate of 30 % per year during the study period.

kerosene and FO) are considered a liquid energy resource in the MARKAL-Bangladesh model. In general, no restrictions are placed on the level of imports.

The cost of imported oil products is linked to world market prices. The prices of oil products are calculated based on Bangladesh Economic Review (BER 2008). In 2005, the average price of FO in Bangladesh was 506 Taka/GJ. It is assumed to increase at a rate of 4.6 % annually reaching 1950 Taka/GJ in 2035 (EIA 2009). The fluctuation in oil prices is not considered in the modeling. CO_2 and SO_2 emission factors are calculated separately for diesel, kerosene and fuel oil products based on the IPCC workbook (IPCC 1996a) and IPCC reference manual (IPCC 1996b).

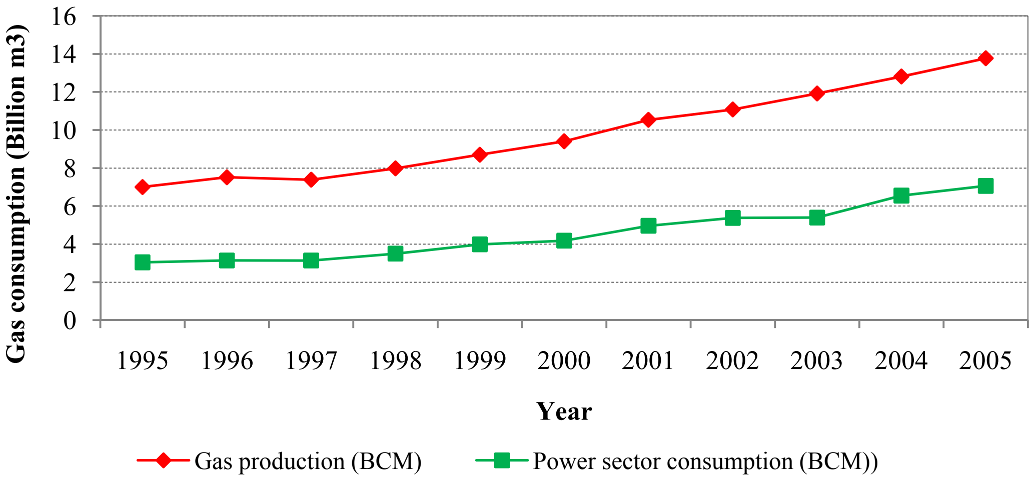

Figure 5.3: Production of natural gas in Bangladesh 1995-2005

5.3 Energy conversion technologies

The energy conversion technologies used worldwide and in Bangladesh for power generation are broadly classified under two categories, namely conventional and non-conventional technologies. They can also be classified as renewable energy technologies (Chapter 3) and non-renewable energy technologies. The latter classification is often preferred, as it directly refers to the depletable energy source or non-depletable kind of energy source and hence has been adopted in this study for the coverage of technologies.

5.3.1 Selected conventional technologies

Steam turbine

The steam turbine (ST) technology has significantly improved over the past decades with respect to performance, reliability and availability. The capacity of a single ST unit has progressed to about 800-1000 MW. In this study, a common and standard unit size of 300 MW is considered using coal and natural gas along with existing ST power plants.

Simple cycle combustion (gas) turbine

The simple cycle combustion turbine (SCGT) technology for power generation is relatively new compared to the ST technology. In a simple cycle (SC) configuration, the exhaust gas from the turbine is released to the atmosphere without utilizing much of its energy. However, the technology is less efficient then the ST technology. SCGT is best suited for burning natural gas. The capacity of a single turbine (one unit capacity) has progressed to more than 300 MW. The efficiency of SCGT has improved and now exceeds 30 %. For application in Bangladesh, a modest range for unit capacity and external features are considered for modeling due to their high reliability and extensive experience throughout the world. Two standard and common unit sizes (100 MW and 150 MW) are used for the modeling.

Combined cycle power plant

Gas turbines are also used in combined cycle (CC) combustion, where the exhaust gas from the turbine is used to generate steam, which is used in a ST to generate additional power. Therefore, by burning the same amount of fuel, a CC gas turbine system generates about 50 % more power than a SCGT system. As a result, the efficiency of a CC power plant is approximately 50 % higher than that of a SCGT. The CC system has become the technology of choice for base-load power generation wherever gas is available. High fuel efficiency and relatively low capital cost make the technology attractive. Another attractive feature of the technology is that a CC power plant can be installed in less time than typical ST plants. In this study, 300 MW plant capacities are considered along with exiting CC power plants.

5.3.2 Conversion technology characteristics

The characteristics of all technologies must be provided to the model. Conversion technologies convert primary energy into final energy carriers. The model requires users to create detailed profiles for two sets of energy conversion technologies: one for converting primary into final energy carriers, and one for converting final energy carriers into energy services. A reasonably representative set of conversion technologies is developed, which includes a total of 20 distinct conversion technology types. For each of the technology types, values are specified for energy input per unit energy output (efficiency), capital cost, fixed and variable operation and maintenance costs, NO_2 and SO_2 emissions per unit of energy output, and the first year in which the technology was introduced (Table 5.4 and 5.5). The characteristics are performance and cost level inputs to the model for 2005 - 2035. For most of the technologies, the performance and cost levels are assumed to be constant over the whole analysis period except for solar PV, where the investment cost is analyzed using technological learning effects. The model determines the capacity level for any technology. In this modeling, the most reliable studies are selected and evaluated to yield a consistent as possible set of cost data.

Table 5.4: Main parameters of conventional conversion technologies (all costs are in 2005 Bangladeshi Taka where 100 Taka = 1.569 USD)

Conversion technology	First year available	Efficiency (%)	Installed cost(million Taka/GW)	Fixed O&M cost (million Taka/GW)	Variable O&M cost (million Taka/PJ)	Reference
Coal steam conventional 250 MW	2010	28.34	66363	267	684	BPDB 2006; Zongwin et al. 2001
Advanced coal steam with flue gas desulphurization (FGD) 300 MW	2015	38.78	87082	443	32	Kaminski 2003; PSMP 2005; Zongwin et al. 2001
Existing FO-based steam power plant	2005	25.91	48960	516	1365	BPDB 2006; MPEMR 2006; Zongwin et al. 2001
Existing diesel-based gas turbine	2005	22.87	35062	753	2875	BPDB 2006; Zongwin et al. 2001
Existing diesel-based diesel generator	2005	22.67	28687	1300	2313	BPDB 2006; PSMP 2005; Zongwin et al. 2001
Existing kerosene-based gas turbine	2005	23.57	35062	753	2875	BPDB 2006; PSMP 2005; Zongwin et al. 2001
Existing gas-based simple cycle (SC)	2005	28.83	22248	204	648	BPDB 2006; PSMP 2005; Zongwin et al. 2001
Gas-based SC 100 MW	2010	28.79	25563	321	44	PSMP 2005; Zongwin et al. 2001
Gas-based SC 150 MW	2010	29.71	22248	321	44	PSMP 2005; Zongwin et al. 2001
Existing gas-based steam turbine (ST)	2005	31	62092	197	251	BPDB 2006; MPEMR 2005
Gas-based ST 300 MW	2010	39.6	62092	321	28	PSMP 2005
Existing gas-based combined cycle (CC)	2005	31.18	42712	179	310	BPDB 2006; PSMP 2005
Gas-based CC 300 MW	2010	46.32	42712	321	35	PSMP 2005

5.3.3 Technology learning

Technology learning is a key driving force of technological change and plays an important role in cost or performance improvement of technologies, simulating the competition and continuous substitution between them in the marketplace. A typical learning curve describes the specific costs of a given technology as a function of the cumulative capacity, a proxy for the accumulated experience (Barreto and Kypreos 2004). It reflects the fact that some technologies may experience declining costs as a result of their increasing adoption, due to the accumulation of knowledge. Theories of learning-by-doing and economics of scale are responsible along with technological breakthrough for these improvements. The cumulative capacity is used as a measure of the knowledge accumulation. The learning effect is represented mathematically by a learning curve which defines the unit cost of a given technology as a function of the cumulative capacity as a measure of the knowledge accumulation (Seebregts et al. 1999). A typical learning curve can be expressed by the following equation:

$$SC(C) = SC_0(C / C_0)^{-b} \tag{5.1}$$

where SC is cost as a function of C, C is the cumulative capacity, b is the learning index (constant), C_0 is the initial cumulative capacity (at t = 0) and SC_0 the initial specific cost (at t = 0).

Various studies have been made to obtain the learning curves for different technologies and to include learning curves in energy system modeling (Messner 1997; Rout et al. 2009; Seebregts et al. 1998; Seebregts et al. 1999; Winkler et al. 2009). According to the findings of the above authors, for each technology there are two distinct phases, i.e., the research, development, and demonstration phase, and the commercialization phase. Technologies belonging to the research, development and demonstration phase are solar PV and wind turbines. Cost reduction in this phase is significant owing to the learning-by-doing and learning-by-using effects.

Three cases were analyzed for modeling the learning effect at IIASA, i.e., the high growth, moderate growth and the ecologically driven case (Messner 1997). The results from the moderate growth case have been adopted in this study, and for the Bangladesh context the following assumptions are made:

1) The learning trend for power generation from solar PV (due to limited potential of other renewable energy technologies) observed internationally will also occur in Bangladesh due to the import of technologies and technical know-how.
2) The path of learning will have a typical exponential shape as commonly recorded.
3) The percentage reduction in the unit cost in Bangladesh will be the same as the percentage projected in the IIASA study over the period of 1990-2050.

The projected investment cost of solar PV obtained is 318750 million Taka/GW in 2005 and decreases to 199609 million Taka/GW by 2035 based on the following equations:

$$GR_{1990-2050,\,IIASA} = \left(\frac{C_{2050,\,IIASA}}{C_{1990,\,IIASA}}\right)^{\left(\frac{1}{60}\right)} - 1 \qquad (5.2)$$

and

$$C_{n,\,Bangladesh} = C_{2005,\,Bangladesh} \cdot (1 + GR_{1990-2050,\,IIASA})^{(n-2005)} \qquad (5.3)$$

where $GR_{1990-2050,\,IIASA}$ is the growth rate of investment cost between 1990 and 2050 (IIASA), $C_{1990,\,IIASA}$ and $C_{2050,\,IIASA}$ are the investment costs in the year 1990 and 2050 (IIASA), $C_{2005,\,Bangladesh}$ and $C_{n,\,Bangladesh}$ are the investment costs in year 2005 and nth year for Bangladesh.

Comments on conversion technologies not covered in this study

A few technologies, e.g., fuel cells, solar thermal, geothermal and tidal, have not been covered in this study mainly due to the following reasons:

1) Technical know-how has not yet matured and spread worldwide. Full-scale commercial activities will take some time to pick them up. At the initial stages, such technologies are expensive. This is important for countries like Bangladesh, where there is a financial crunch restricting the freedom of experimenting with new technologies.
2) In the case of technologies like solar thermal power, better uses like water heating, crop drying, etc., exist that are more accepted and better proven than power generation. However, a few solar thermal power plants are operation in some countries, but most of them are more in the form of pilot projects than commercial ventures.
3) Know-how on other technologies like geothermal, tidal and wave energy exists, and Bangladesh needs to investigate their potentiality. However, a limited supply of technologies and other technical barriers hinder their application in Bangladesh.

Table 5.5: Main parameters of renewable energy technologies (all costs are in 2005 Bangladeshi Taka where 100 Taka = 1.569 USD)

Conversion technology	First year available	Efficiency (%)	Installed cost (million Taka/GW)	Fixed O&M cost (million Taka/GW)	Variable O&M cost (million Taka/PJ)	Reference
Existing hydro	2005	100	95625	443	10	BPDB 2005, 2008
Large hydro >50 MW	2015	100	127500	443	10	BPDB 2005, 2008
Biomass bagasse-fired power plant	2010	22.67	35700	2231	-	APEC 2002; Hasan 2006
Biomass solid waste gasification	2015	25	71655	2805	-	APEC 2002; Khatun 2008
Biomass rice	2010	22.67	91800	5227	-	IDCOL 2006
Biomass poultry waste	2010	25	157781	18900	-	APEC 2002; Zaman 2007
Solar PV centralized	2010	100	298893	3085	-	NEA 2005) Shafiei et al. 2009
Wind centralized	2010	100	63750	1511	-	Nguyen 2007a; Nguyen and Ha-Duong 2009; Rout et al. 2009

5.4 Generic details

Besides the technical and financial parameters related to different stages of RES of the Bangladesh power sector, the following parameters are also required by MARKAL:

1) Base year: 2004 - 2005 is taken as the base year. This is indicated as year 2005 in this study, as MARKAL accepts just one year as a parameter.
2) Duration of study: A 30-year period is covered in this study, which is a period covered in most of the similar studies, although some short-term studies covering a 20-year time span have also been conducted. However, as MARKAL is considered to be more useful for longer term analysis, the 30-year horizon was selected, especially since the degree of uncertainty related to technology and economic parameters increases with longer time spans.
3) Length of periods: The 30-year span is divided into 6 periods of 5 years each.
4) Discount rate: A financial discount rate of 10 % per year is considered. The current rates of interest payable on ‘fixed deposits of money’ in nationalized banks are close to 10 %, and this was the main reason for using this value.
5) The main purpose of all the power plants covered in this study is to feed the electricity grid. In industrial countries, however, renewable energy systems like

solar and wind power plants are mainly used to reduce the load duration on conventional power plants during various times of the day (Mathur et al. 2003). In the case of Bangladesh, there is always a possibility of consumption of additional power, as economic growth is not stable, and the growth of many sectors is restricted due to shortage of power.

6) No heating load is considered to be met through the heat rejected in the energy conversion processes.

7) Transmission and distribution (T&D) loss amounted to 21 % of the generated electricity in 2005 (BBS 2008; BER 2006). It is considered that the losses will decrease to 15 % by 2035.

8) It is assumed that all the existing power plants of the base case year will continue to work throughout the whole analysis period. Considering this assumption is particularly valid in Bangladesh because even very old power plants are kept in working condition with necessary maintenance and minor furnishing.

9) An overall GDP growth of 6.8 % is considered (GSMP 2006). This assumption, however, is not directly imported but governs the trend of the increase in energy demand.

10) The costs of the power plants are taken from Bangladesh sources rather than converting the costs in other countries into Bangladesh Taka. This is because costs in other countries may have some extra hidden cost that may not be relevant in Bangladesh.

11) The study considers three main greenhouse gases: CO_2, NO_2 and SO_2. Since appropriate national emission factors are not available, the emission coefficients of the IPCC reference approach has been adopted (IPCC 1996a, 1996b).

12) In MARKAL, the electric load profile can be differentiated according to three seasons: intermediate, summer and winter, which in turn are distinguished between day and night. The peak load in summer at 7 PM is adopted in the modeling.

13) As the focus of this study is power generation capacity and utilization, stages like end-use technologies (lighting load, cooling load. etc.) have been merged into their respective sector-wise electricity demand. The sector-wise demand

does not represent end-use demand, but addresses the gross demand of each sector, and details related to the end-use application stage are not required for this modeling exercise. Similarly, the cost of fuel extraction and other similar figures have not been specified separately, as the final costs of fuel for the power plants, which include the costs in all previous stages, are considered directly.

5.4.1 Assumptions and boundaries of the study

The following general assumptions are important to understand the MARKAL-Bangladesh model:

1) Only the centralized grid is covered in the MARKAL modeling.
2) Daily load fluctuations are not considered.
3) All existing and working power plants at the beginning of the base year will continue to work throughout the study period.
4) There is no constraint regarding availability of financial means due to private sector investment in the power sector.
5) All prices and costs are indicated in Bangladesh Taka.
6) It is assumed that sufficient infrastructure support will be present regarding manufacturing, transportation, etc.
7) Efficiencies and specific emission values correspond to full load operation of power plants.

5.5 Reference energy system of Bangladesh power sector

Based on the above-specified data, the reference energy system of Bangladesh can be built, i.e., the MARKAL-Bangladesh model. This reference system can be illustrated in a network diagram indicating energy flows and the associated process parameters of technologies employed in various stages (source to end use) of the total energy system (Figure 5.4).

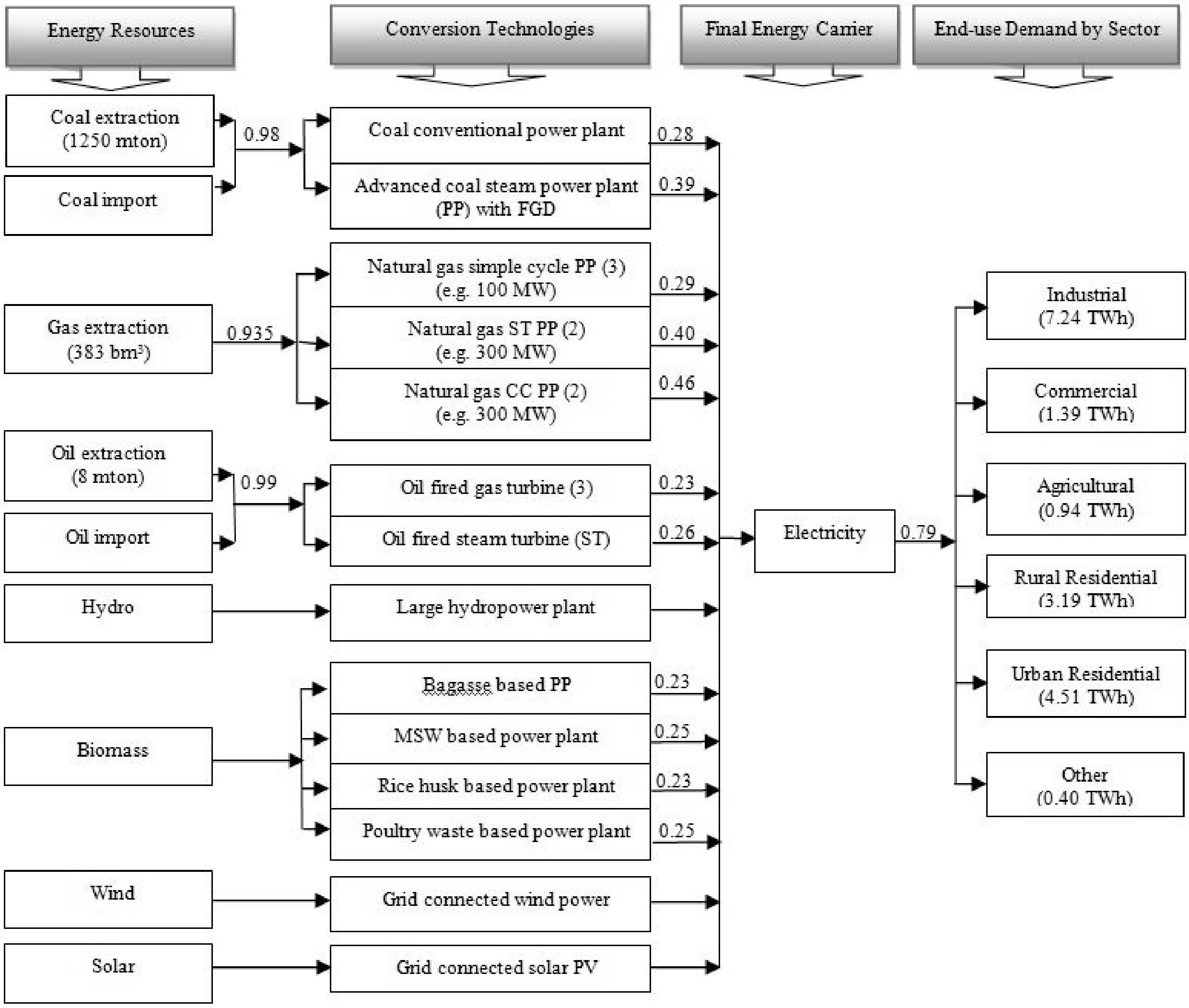

Figure 5.4: Simplified reference energy system of the Bangladesh power sector (values indicate proven reserves, conversion & transmission efficiency, and demand in 2005, mton = million tons, bm^3 = billion m^3, PP = power plant, ST = steam turbine, FGD = flue gas desulphurization, CC = combined cycle)

6 SCENARIO DEVELOPMENT AND RESULTS

6.1 Scenario development

Scenarios are like storylines to predict the future within a possible range of existence. Researchers agree to the fact that future events related to technological development or economic growth cannot be predicted accurately. These are usually associated with some uncertainty due to unpredicted events or landmarks that decide a path of growth for future techno-economic scenes. However, major possibilities are usually known and should be incorporated in any future planning. Therefore, the scope of this study has also been to cover major possibilities in the form of different scenarios (Figure 6.1). These scenarios represent those factors most likely to affect the future development of renewable energy technologies in the Bangladesh power sector. Important exogenous model specifications for these scenarios include the demand trajectories derived from overall macro-economic projections, energy supply limitations, energy prices, technology cost and performance parameters, bounds on technology penetration, and environmental characteristic.

The scenarios in this study are based on three cost minimization aspects, with the aim of mainly curbing the CO_2 emission in the power sector: 1) simple cost minimization, which covers the commercial aspects related to various technologies like investment, operation and maintenance (O&M) costs under the defined set of constraints in which no artificial measures are taken to curb environmental degradation, 2) cost minimization through a CO_2 emission reduction target, and 3) cost minimization through carbon[7] taxes. All scenarios are compared with the base scenario.

[7] A carbon tax can be translated into a CO_2 tax, since a ton of carbon corresponds to 3.67 tons of CO_2.

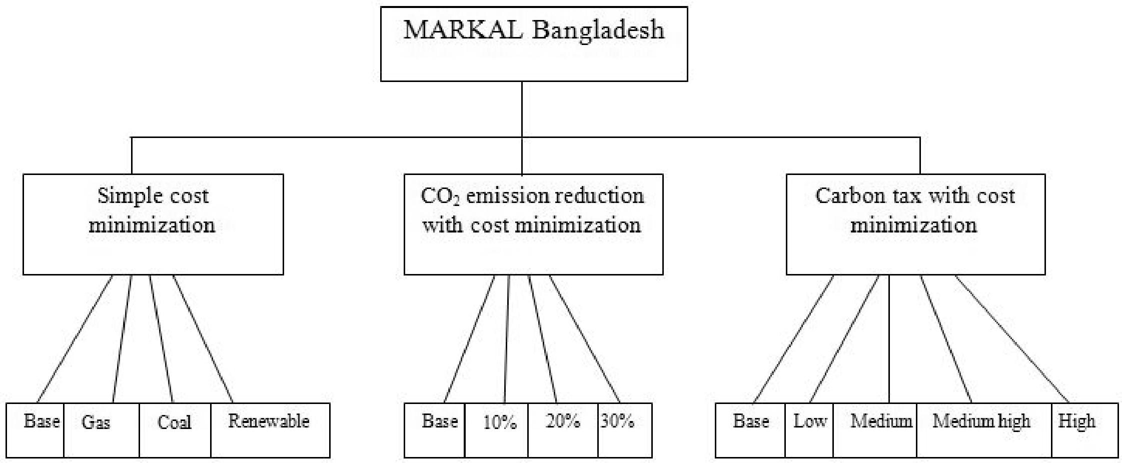

Figure 6.1: Structure of applied scenarios

The following 11 scenarios are investigated:

Scenario 1: Base scenario (Base)

Scenario 2: Limited gas scenario (Limited gas)

Scenario 3: Scenario with null coal import (Null coal import)

Scenario 4: Scenario with accelerated renewable energy penetration (Renewable target production)

Scenario 5: Scenario with 10 % CO_2 emission reduction from 2015 onwards compared to base scenario CO_2 emission (CO210)

Scenario 6: Scenario with 20 % CO_2 emission reduction from 2015 onwards compared to base scenario (CO220)

Scenario 7: Scenario with 30 % CO_2 emission reduction from 2015 onwards compared to base scenario (CO230)

Scenario 8: Scenario with carbon tax of 1500 Taka per ton CO_2 (Low tax)

Scenario 9: Scenario with carbon tax of 3000 Taka per ton CO_2 (Medium tax)

Scenario 10: Scenario with carbon tax of 6000 Taka per ton CO_2 (Medium-high tax)

Scenario 11: Scenario with carbon tax of 12000 Taka per ton CO_2 (High tax)

6.2 Scenario description

6.2.1 Base scenario

The base scenario presumes a continuation of current energy and economic dynamics and provides a reference for comparing impacts of future policies. This scenario is based on an understanding of how the energy sector dynamics and specifically power sector dynamics have been evolving in the past as well as on an analysis of the present situation and most likely the future trajectory. It incorporates changes in the economic growth rates and growth patterns, structural changes in the economy, changes in consumption patterns, rates of technological progress, penetration of innovated technologies, alternations in energy supply and energy prices, dependence on foreign imports, enforcement of environmental laws and regulations, initiation and success of institutional changes and policy interventions affecting the energy sector in general and the power sector in particular. The main assumptions and parameters of this case have already been defined in the previous sections including technology learning effects, constraints on resources and different technologies bound growths.

6.2.2 Limited gas scenario

The limited gas scenario examines the overall system in the case where a fix amount of natural gas is available for power generation. Instead of using the cumulative total proven reserve of gas for power generation as in the base scenario, it is considered that natural gas production continues until the end of the analysis period based on more or less the present limited capacity. Reason behind this assumption is the government of Bangladesh intends to explore offshore gas, and there is a high probability that gas reserves will be found and can be used for power generation. As the demand for gas in different sectors is increasing, it is assumed that the gas available for power generation is 250 PJ in 2005 with a maximum of 325 PJ in 2015, which decreases to 200 PJ by 2035.

6.2.3 Null coal import scenario

The null coal import scenario assumes a specific policy intervention in the import of fossil fuels. The intention is to use all available energy resources and reduce the import of coal for electricity generation. This constraint specifies that there is no imported coal available for power generation.

6.2.4 Renewable target production scenario

The renewable target production scenario assumes specific policy interventions to accelerate deployment of renewable energy technologies. Specific national targets are set for supplying a certain percentage of the total power generation from renewable energy sources. The government targets of electricity generation using renewable energy technologies of 5 % of the total power generation by 2015, 10 % by 2020 (REP 2008) and 20 % by 2035 are applied. It is assumed that manufacturing capabilities in the country will be developed and import restrictions for deployment of advanced technologies like solar PV eased. Bound growth and learning costs for solar PV are already introduced in the base scenario.

6.2.5 CO_2 emission reduction scenarios

Presently, global warming and mitigation of greenhouse gases (GHGs) are the major issues of international concern. The power sector is major source of CO_2 emission and accounts for about 36 % of the total CO_2 emission in the world, 45 % in Asia and 40 % in Bangladesh (Shrestha et al. 2009). The power sector CO_2 emission has been increased at an average annual rate of 8.5 % from 1990 to 2004 in Asia as a whole (Shrestha et al. 2009).

Rising energy demand has lead to rapidly increasing GHG emissions from electricity generation in Bangladesh. Due to the large share of fossil fuels in the energy mix, the Bangladesh economy produces high CO_2 emissions, which are likely to rapidly increase. In this case, it is necessary to develop and promote alternative energy sources that ensure energy security without increasing environmental impacts. It is also interesting to explore the potential of the Bangladesh energy system to meet national emission targets along with mitigation costs.

Since developing countries are not obliged to reduce GHG emissions, studies in evaluating the impacts or co-benefits of GHG mitigation policies in developing countries are lacking (Shrestha and Pradhan 2010). For a developing country like Bangladesh, the evaluation of the impacts of GHG mitigation policies in the power sector would provide a basis for more comprehensive technological choice, and economic and environmental analysis. Such an evaluation would also support climate change mitigation policies aimed at sustainable power-sector development as part of the efforts to address the climate change issues identified in the United Nations Framework Convention on Climate Change (UNFCCC), which Bangladesh has already ratified.

Three CO_2 emission reduction targets are imposed in the CO_2 emission reduction scenario: 10 % (scenario 5, CO210), 20 % (scenario 6, CO220) and 30 % (scenario 7, CO230) CO_2 emission reduction from 2015 onwards compared to the base scenario emission level. It insures one of the objectives of the Bangladesh energy policy to ensure environmentally sound sustainable energy development programs and environmentally compatible electric energy (NEP 2004&2008) and the ultimate objectives of UNFCCC are to achieve stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate (Dutt and Glioli 2007; SAR 1996).

6.2.6 Carbon tax scenarios

The Kyoto Protocol to the UNFCCC has set legally binding reduction targets for GHG emissions for the countries listed in its Annex II[8] and introduced three international flexibility mechanisms, namely international emission trading, joint implementation, and the Clean Development Mechanism (CDM) which are defined in the Article 12 of the Kyoto Protocol, Annex I[9] countries can participate in the implementation of projects that reduce GHG emissions in non-Annex I[10] countries. The GHG emission reductions achieved by implementation of such projects as compared with the emissions in a base scenario, duly certified, are treated as certified emission reductions, which can be bought and used by the Annex I countries to comply with their emission reduction commitments (Dutt and Glioli 2007).

Bangladesh participation in the global carbon market through the CDM depends on the global carbon price. CO_2 emission reduction domestically at low cost, i.e., at costs that are significantly lower than the carbon price, will provide opportunities to generate substantial contribution from participation in the global carbon market. While the Kyoto Protocol has not proposed any binding emission limitation commitments for developing countries, instruments such as CDM and the possibilities

[8] Annex II countries consist of the OECD members of Annex I excluding the Economies in Transition (the EIT parties).
[9] Annex I countries consist of the industrialized countries that were members of the OECD in 1992 and the EIT parties.
[10] The non-Annex I countries are mostly developing countries.

of emission trading are likely to provide economic incentives for significant emission mitigation in developing countries like Bangladesh. In this context, issues related to compliance of developing nations to participate in GHG adaptation and mitigation activities and setting up of related business opportunities need to be kept in mind. A carbon tax is considered to favor low-emission power generation projects and discourage high-emission activities. Bangladesh promotes renewable energy projects through subsidies. These subsidies could be paid for through a tax on coal and other fossil fuels. The additional tax revenue would allow increases in the subsidies for renewable energy and other low energy technologies (Dutt and Glioli 2007)

Therefore, four different rates of carbon tax are considered in this study namely low tax (1500 Taka per ton CO_2, scenario 8), medium tax (3000 Taka per ton CO_2, scenario 9), medium-high tax (6000 Taka per ton CO_2, scenario 10) and high tax (12000 Taka per ton CO_2, scenario 11).

6.3 Results

6.3.1 Simple cost minimization

In the base scenario, the total generation capacity is expected to increase from 10.6 GW in 2010 to 57.3 GW in 2035, i.e., at an average growth rate of 7 % (Table 6.1). At the same time, the generation structure changes significantly. The share of gas-based power plants reduces from 90 % (9.6 GW) in 2010 to 39 % (22.5 GW) in 2035 in total capacity, whereas the increase in the share of coal-based power plants 2.34 % (0.3 GW) in 2010 to 50 % (28.7 GW) in 2035 is extremely high. The switch from gas- to coal-based power plants leads to a strong increase in coal consumption, 3.3 PJ in 2010 to 1784.3 PJ in 2035, i.e., at an average growth rate of 28.7 %. This coal consumption rate is higher than the domestic availability. Thus, the country would need to import energy resources such as coal from 2025 onwards to meet the required demand. The proportion of imported coal in the total fuel consumption would increase substantially from 18 % (208.4 PJ) in 2025 to 54 % (1049.3 PJ) in 2035. This deficiency would have adverse impacts on the country's balance of payment and the availability of foreign currency resources.

The model predicts that electricity production is dominated by advanced coal steam with flue gas desulphurization (FGD) power plants. In the base case, the coal

FGD produces electricity amounting to 24 % (14 TWh) in 2015 and 84 % (189 TWh) in 2035 of the total generation due to the unused capacity of oil-based power plants in the analysis period and limited gas resources. As gas is the cheapest energy, the model suggests using gas in the early period. As there is no alternative, it selects the efficient coal-based FGD plants in the later period. As the potential of wind and biomass is limited and investment costs are relatively high, the model allocates the upper bound production of these technologies only in 2035. Due to the highest investment cost of solar PV, this form of energy is not selected in the base scenario. As the running costs of hydro power are lower, the model allocates the upper bound production of hydro.

Table 6.1: Capacity development and fuel requirements in the base scenario

	2010	2015	2020	2025	2030	2035
Total capacity (GW)	10.64	14.16	22.99	31.28	42.76	57.26
Coal conventional power plant	0.25	0.25	0.25	0.25	0.25	0.25
Advanced coal steam with FGD	0	1.89	10.16	13.93	21.94	28.48
Oil-based power plant	0.5	0.5	0.5	0.5	0.5	0.5
Natural gas simple cycle and steam turbine	3.98	3.98	3.98	3.42	3.28	3.28
Natural gas combined cycle	5.61	7.02	7.02	11.33	12.14	19.19
Hydro	0.23	0.33	0.55	0.55	0.55	0.55
Solar PV	0	0	0	0	0	0
Biomass	0.05	0.12	0.25	0.28	0.3	0.4
Wind	0.02	0.07	0.28	1.02	3.8	4.61
Fossil fuel requirement (PJ)	320.43	524.79	814.56	1139.47	1494.3	1940.25
Domestic coal	3.25	134.25	683.63	735	735	735
Imported coal	0	0	0	208.38	622.22	1049.33
Natural gas	317.18	390.54	130.93	196.09	137.08	155.92
Imported oil	0	0	0	0	0	0

In the limited gas scenario (referred to hereafter as “gas scenario”), the total generation capacity is expected to increase from 10.3 GW in 2010 to 54 GW in 2035, i.e., at an average growth rate of 6.8 % (Figure 6.2). Power generation from gas-based combined cycle (CC) power plants decreases by 1.1 GW, 0.6 GW and 2.1 GW in 2015, 2025 and 2035, respectively, and increases by 0.3 GW, 0.1 GW and 1.1 GW in 2010, 2020 and 2030 compared to base scenario. The capacity level of advanced coal FGD power plants decreases by 2.8 GW, 1. GW, 2.9 GW and 1.1 GW in 2020, 2025, 2030 and 2035, respectively. In this scenario, other technologies capacity levels are kept at the same level as in the base scenario. Electricity generation from coal power plants decreases by 136 TWh between 2005 and 2035 (Figure 6.3). Consequently, electricity production by gas-based power plants increases by 127 TWh and by oil-based power plants by 9 TWh between 2005 and 2035.

The contribution of solar energy increases significantly in the renewable energy target production scenario (referred to hereafter as "renewable scenario"), reaching almost 14.2 GW by 2035. A total capacity of 71.5 GW is expected by 2035. The capacity level is higher than in the base scenario because of the high capacity of solar PV penetration in the power generation system. Advanced coal FGD still dominates in this scenario (28.7 GW), followed by gas (22.5 GW) and solar PV (14.2 GW) in 2035. Electricity generation capacity by coal power plants is expected to decrease from 389.5 GW in the base scenario to 378.3 GW between 2010 and 2035. Electricity generation from coal FGD power plants decreases from 2585 TWh to 2252 TWh between 2015 and 2035. Solar PV generates total about 319 TWh between 2005 and 2035 (Figure 6.3). Generation from biomass and gas-based CC power plants slightly increases during the study period. The total renewable capacity level increases from 0.5 GW in 2010 to 19.8 GW in 2035 in the renewable scenario (Figure 6.4).

The scenario total power generation capacity level under null coal import (referred to hereafter as "coal scenario") is about 100.6 GW in 2035. The capacity level is higher than in the other scenarios because of the high capacity of solar PV penetration in the power generation system. In this scenario, the total renewable generation capacities increase dramatically to about 46.6 GW by 2035. Under this constraint, oil-based power plants are also selected in 2035. Coal power plants are replaced by 7.8 GW oil-based power plants and 41 GW total renewable-energy-based power plants in 2035 compared to the base scenario. This reduces electricity generation from coal power plants by 21.7 TWh (22 %), 65.5 TWh (46 %) and 110.6 TWh (59 %) in 2025, 2030 and 2035, respectively, compared to the base scenario. Electricity generation from solar PV is expected to grow from around 0.2 TWh in 2010 to 84.1 TWh in 2035 with an average growth rate of 27.1 %, where the allowed growth rate is 30 %. Oil-based power plants would be selected in the later period (2030 - 2035) in this scenario due to the limited natural gas resource and also due to increase in demand. Fossil-fuel-based technologies will be necessary, as renewable energy technologies cannot cater for the entire future demand. The technology learning cost for solar PV enhances competitiveness of the technologies and leads to a higher rate of implementation of solar PV in the analysis period.

The results of each scenario show that in the base scenario and gas scenario, there is no production from solar PV technology. In the renewable and coal scenarios, solar PV plays an important role in the generation of electricity, and the capacity is expected to grow by 14.2 GW and 40.8 GW, respectively, by 2035. Other renewable energies reach their allowed maximum capacity levels in these scenarios.

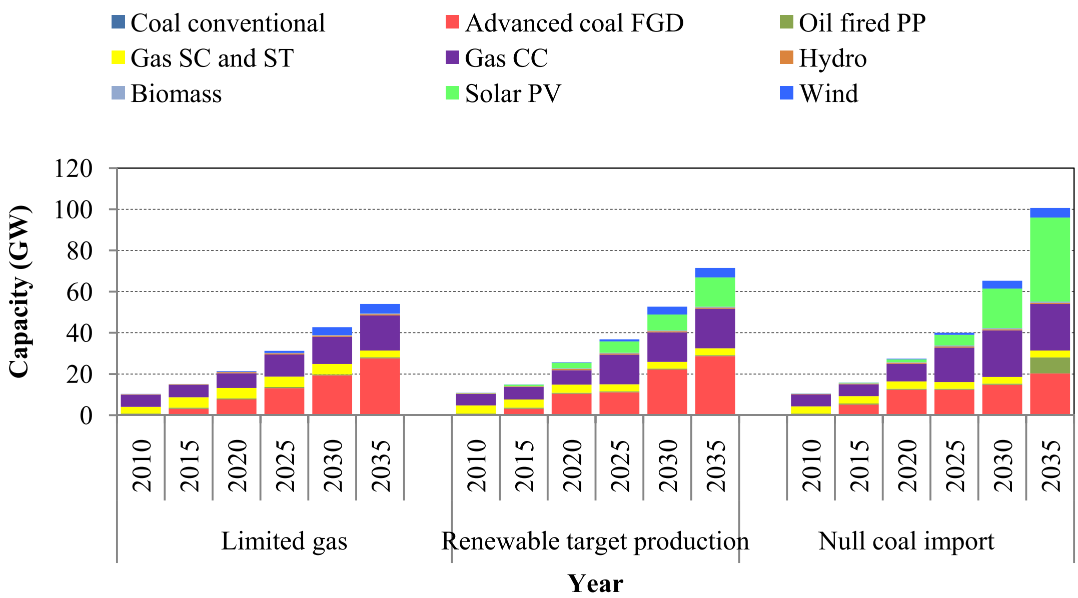

Figure 6.2: Technology capacity level in GW by year in the limited gas, renewable target production and null coal import scenarios (SC = simple cycle, ST = steam turbine, FGD = flue gas desulphurization, CC = combined cycle, PP = power plant and PV = photovoltaic)

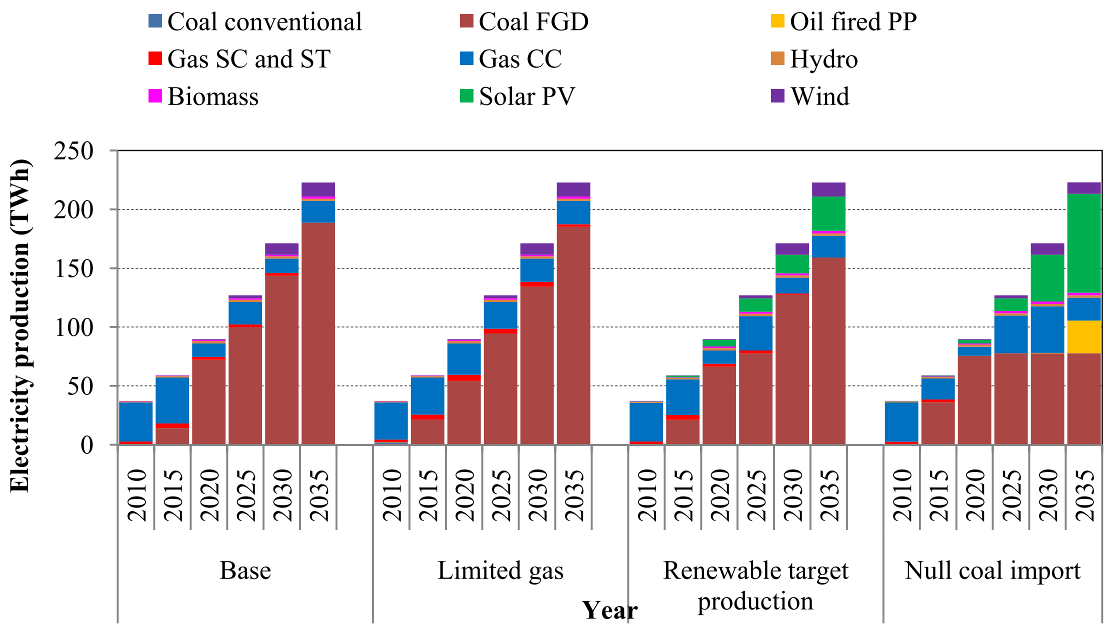

Figure 6.3: Electricity production in TWh by technology by year in base, limited gas, renewable target production and null coal import scenarios

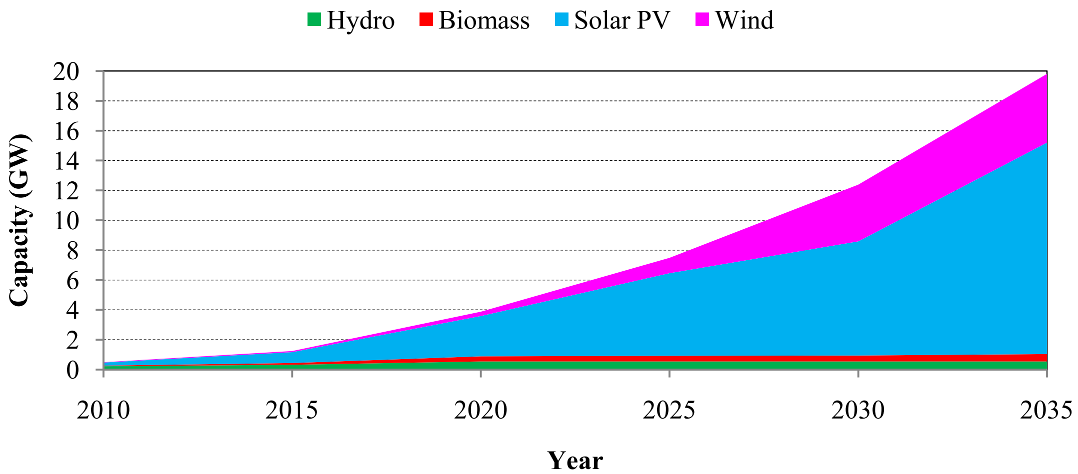

Figure 6.4: Projections of renewable energy capacities in GW in the renewable scenario

Renewable energy technologies in the power sector grow faster than the overall generation capacity in the renewable and coal scenarios. The intervention of these policy scenarios causes significant changes in the renewable energy trajectories compared to the base scenario (Table 6.2 and Figure 6.5). In the base scenario, their share in overall capacity increases from 4.1 % in 2005 to 9.7 % in 2035. The analysis shows a substantially higher implementation of renewable energy technologies compared to the base scenario. The capacity shares of renewable generation in the base and gas scenarios are almost same from 2005 – 2030, while they slightly decrease from 2030 – 2035 as more gas is available in the later period compared to the base scenario. The renewable scenario shows a 2.4 times higher renewable energy production capacity by 2015, about 4 times by 2025 and about 3.6 times by 2035. However, in the coal scenario, there is a much higher degree of renewable technologies implementation with a more than 8-fold capacity increase in 2035 over the base scenario. This coal scenario shows a renewable energy generation capacity of 5.7 %, 18 % and 46 % in 2015, 2025 and 2035, respectively, of total power generation.

Table 6.2: Renewable generation capacities across the simple-cost minimization scenarios in GW

Scenario	2010	2015	2020	2025	2030	2035
Base	0.3	0.52	1.08	1.85	4.65	5.56
Limited gas	0.3	0.52	1.08	1.65	4.65	5.56
Renewable target production	0.5	1.25	3.88	7.49	12.4	19.82
Null coal import	0.4	0.9	2.48	7.23	24.1	46.6

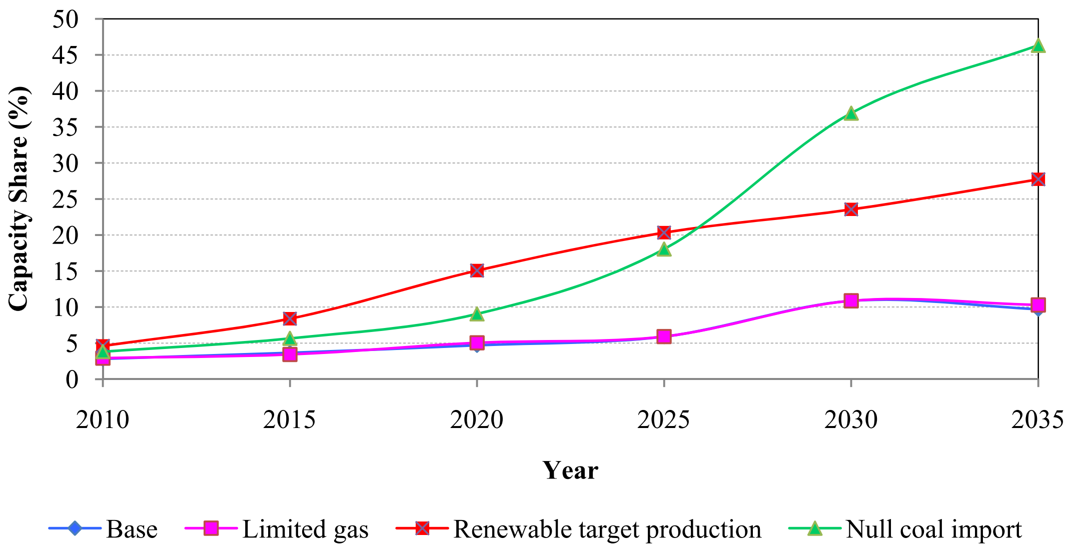

Figure 6.5: Share of renewable energy in overall power generation capacity

The analysis results reveal that a cumulative CO_2 emission from the entire energy system in the base scenario is approximately 2410 million tons between 2005 and 2035. It reaches 18.25 million tons in 2010 and is expected to increase to 160 million tons in

2035. Per capita, the increase would be from 0.3 tons in 2010 to 2 tons in 2035 (considering 40 % emissions from the power sector and 60 % from other sectors), equivalent to a growth rate of 7.8 % per year. Compared to the CO_2 emission in developed and some developing countries, these figures are still quite low (the CO_2 emission per capita in 2000 in Germany was 9.6 tons, France 6 tons, UK 9.3 tons, China 2.19 tons and India 1.1 tons; (WB 2007). However, if the increase continues, in only 20 years from the end of the analysis period in 2035, the CO_2 emission per capita of Bangladesh will reach that of Germany in 2000. Therefore, appropriate measures need to be taken in the power sector to control the CO_2 emissions.

The gas scenario reduces the overall energy system CO_2 emission by only 28 million tons between 2005 and 2035 compared to the base scenario. CO_2 emission reduces by 300 million tons between 2005 and 2035 in the renewable scenario. In the coal scenario, it reduces by a total 644 million tons between 2005 and 2035, i.e., by 3 % in 2020, 18 % in 2025, 40 % in 2030 and 48 % in 2035 compared to the base scenario.

The discounted energy system costs (referred to hereafter as system cost) represents the total cost for the entire analysis period 2005-2035 for investments in energy conversion technologies, fuel, O&M, and other costs. In the gas scenario, the total system cost slightly increases from 2881 billion (2005) Taka to 2917 billion Taka, which is about 1 % higher than in the base scenario (Figure 6.6). Import dependency on fossil fuels based on the base scenario value 100 % drops to 90 %, 66 %, and 21 % in the gas, renewable and coal scenarios, respectively, but leads to an increase in the total system cost. The model results show that the system cost rises to 3255 billion Taka and 3568 billion Taka by an overall percentage increase of 13 % and 24 % in the renewable and coal scenarios, respectively, compared to the base scenario. The system cost in the coal scenario is relatively high due to high investments in solar PV generation and imported fuel oil to meet the total energy demand. At the end of the analysis period (2030 - 2035), the system costs in the renewable scenario are almost the same as in the base scenario. In contrast, in the coal scenario the system costs increase over the long-term period compared to the base scenario due to high investments in fuel oil imports, insufficient renewable energy, and limited gas availability. The model shows that the best solution is to increase the investments in efficient coal FGD plants between 2015 and 2020 immediately after their introduction in the base, renewable and coal scenarios.

The peak system cost is in 2020 in the renewable scenario due to higher investments in solar PV to meet the required percentage level of renewable energy.

Furthermore, the results show that the increase in total system cost for reduction of cumulative CO_2 emissions over the study period is around 1066 Taka/ton in the coal scenario and 1250 Taka/ton in the renewable scenario.

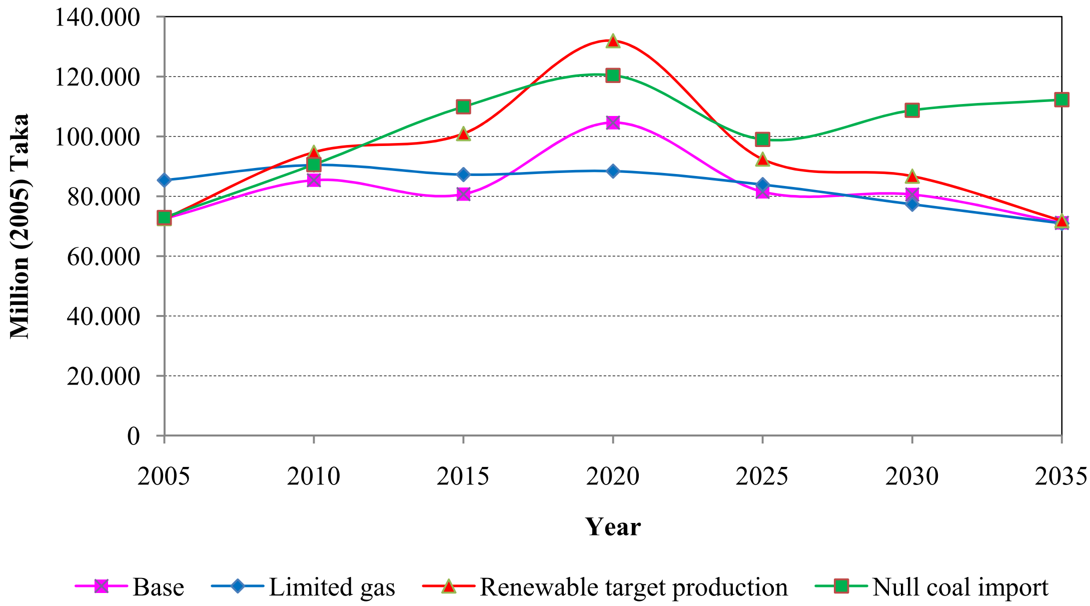

Figure 6.6: Total energy system costs for investments in energy conversion technologies, fuel, operation and maintenance in million Taka by year in the base, limited gas, renewable target production and null coal import scenarios

6.3.2 Environmental cost minimization

CO_2 emission reduction target scenarios

The introduction of the CO_2 emission reduction targets (the reductions of 10 %, 20 % and 30 % CO_2 are referred to hereafter as CO210, CO220 and CO230, respectively) directly affect the shift of technologies from high carbon content fossil-based to low carbon content fossil-based and clean renewable energy-based technologies. As a result of emission reduction targets, power generation based on solar PV is introduced and its generation capacity gradually increases during 2010 – 2035. Compared to the base scenario, 12.7 GW, 21.4 GW and 30.1 GW solar PV-based generation capacities are additionally selected in 2035 in the CO210, CO220 and CO230 scenarios, respectively. Solar PV generation starts with a capacity of 0.1 GW in 2010 in the CO210 scenario and grows at a rate of 24.7 % per year. In the CO220 and CO230 scenarios, the from solar PV generation starts with a capacity of 0.5 GW and 1.4 GW in 2010 and a growth rate of 16.2 % and 13.1 % per year, respectively. The total generation capacity is expected to increase from 10.6 GW in 2010 to 84.7 GW, 92.6 GW and 101.5 GW in 2035 in the CO210, CO220 and CO230 scenarios, respectively (Figure 6.7). The generation capacity is relatively higher in the CO_2 emission reduction scenarios than in the base scenario due to implementation of a higher solar PV capacity, which generates electricity only during the day.

Gas-based CC power plant capacity increases significantly in the short-term period (2005 - 2020) in all emission reduction scenarios compared to the base scenario. The model reveals that the least-cost solution is to use the limited gas reserves in the short-term period, although the gas-based CC plants are mostly unused in the long-term period (2025 - 2035) (Figure 6.8). That is why the power generation capacity based on coal FGD increases significantly in the later period (2025 - 2035) in the CO_2 emission reduction scenarios compared to the base scenario. Due to high oil prices, oil-based power plants do not receive higher allocation in the CO_2 emission reduction target scenarios. Fossil fuel-based technologies would be required, as renewable energy technologies cannot cater for the entire future energy demand. The learning cost for solar PV enhances competitiveness of the technologies and leads to a higher rate of implementation of this technology in the analysis period.

Between 2015 and 2035, after the introduction of emission mitigation targets, i.e., 10 %, 20 % and 30 % CO_2 reduction, electricity generation by coal power plants reduces from 2585 TWh to 2324 TWh, 2046 TWh and 1763 TWh, i.e., by 10 %, 21 % and 32 % respectively, compared to the base scenario (Figure 6.8). This type of electricity generation is replaced by renewable energy technologies. In the base scenario, the expected electricity generation from renewable technologies is about 210 TWh between 2005 and 2035; it is expected to increase by 431, 709 and 995 TWh in the CO210, CO220 and CO230 scenarios, respectively, during the study period.

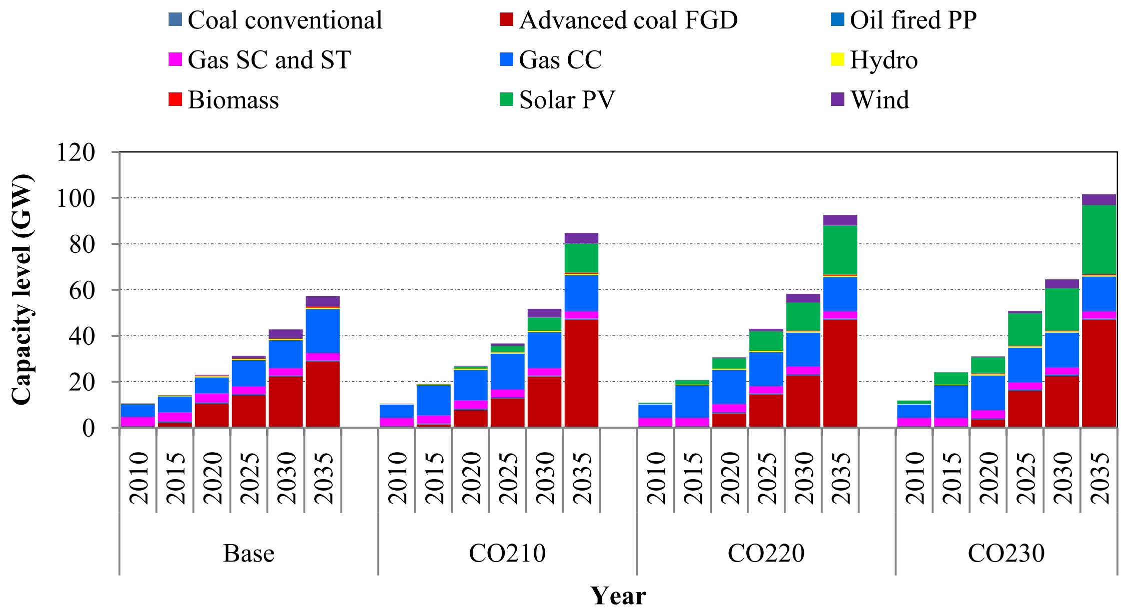

Figure 6.7: Technology capacity level in GW in the base and all CO_2 emission reduction targets by year (SC = simple cycle, ST = steam turbine, FGD = flue gas desulphurization, CC = combined cycle, PP = power plant and PV = photovoltaic)

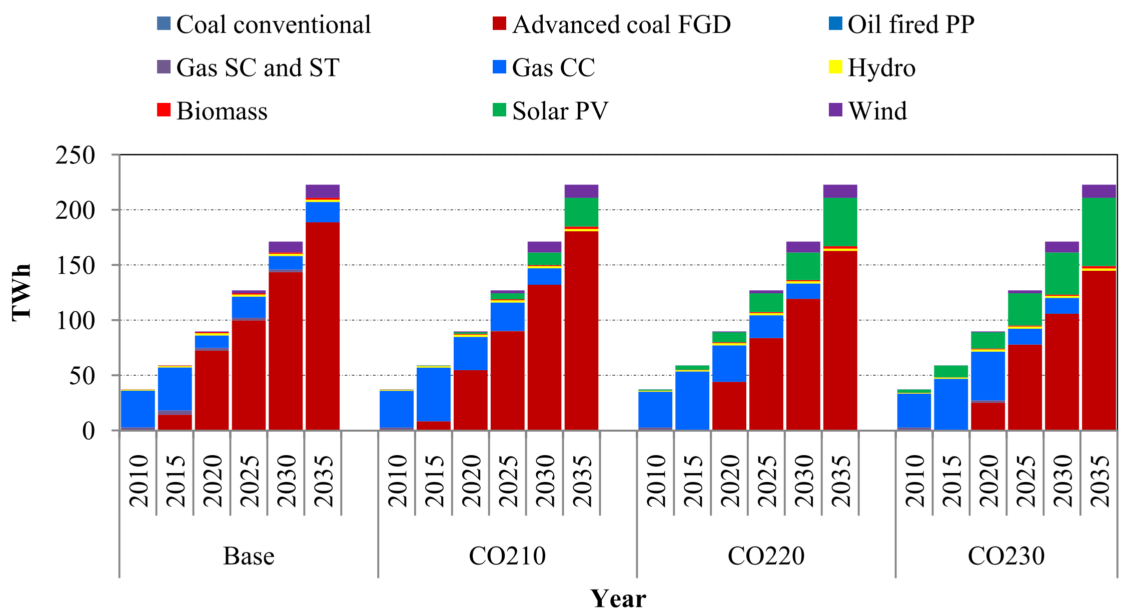

Figure 6.8: Electricity production in TWh by technology and year in the base and all CO_2 emission reduction targets

To summarize the extensive results generated for each of the CO_2 emission reduction target scenarios by the MARKAL-Bangladesh model, the primary energy mix in 2035 is selected as the principal metric (Figure 6.9). This provides a good indication of the types of choices made by the model to meet the various CO_2 emission reduction targets applied. The colored bars (except yellow in the middle) in the Figure 6.9 provide the breakdown of primary energy use for the base scenario in 2005 and all scenarios in 2035. The numbers above each bar indicate the total and percentage of the cumulative imported coal and the total cumulative and percentage of CO_2 emission reduction compared to the base scenario during the study period. Oil is not indicated, as it is not selected for power generation during the study period. The center yellow bar in the three scenarios on the right in this figure shows the change in cumulative total system costs relative to the base scenario. Due to the large uncertainties in this kind of analysis, the percentage change in system costs between the various scenarios as the measure of the cost impact of the changes imposed by each scenario is applied. The system cost for the base scenario is the reference cost in all cost comparisons. In the base scenario, no constraints were placed on CO_2 emission reduction.

CO_2 emission reduction targets have positive impacts on the energy security of the country. The energy security issue is analyzed in terms of changes in net energy import dependency and diversification of energy resources resulting from the selected CO_2 emission reduction targets. The CO210 scenario allows a reduction in imported coal use of about 15 % contributing an only 8.8 % increase in system costs during 2005-2035. Coal imports average 313 PJ per year in the base scenario during the 30-year study period, peaking at 1050 PJ in 2035. Import dependency reduces by 33 %, and 52 % in CO220 and CO230 scenarios, respectively, compared to the base scenario during the study period, but led to an increase in the total system costs of 25 % and 45 %. Alternatively, import dependency based on the base scenario value 100 %, drops to 85 %, 67 %, and 48 % in the CO210, CO220 and CO230 scenarios, respectively (Figure 6.9). On the other hand, the system cost increases by 2.5 %, 8 % and 9 % in 2035 in these scenarios, respectively (Figure 6.10). The system costs increase significantly in the early period (2005-2020) due to high investments in the deployment of solar-PV-based power generation. The system costs decrease in the later period (2020 – 2035) due the effects of the high investments in renewable technologies in the early period.

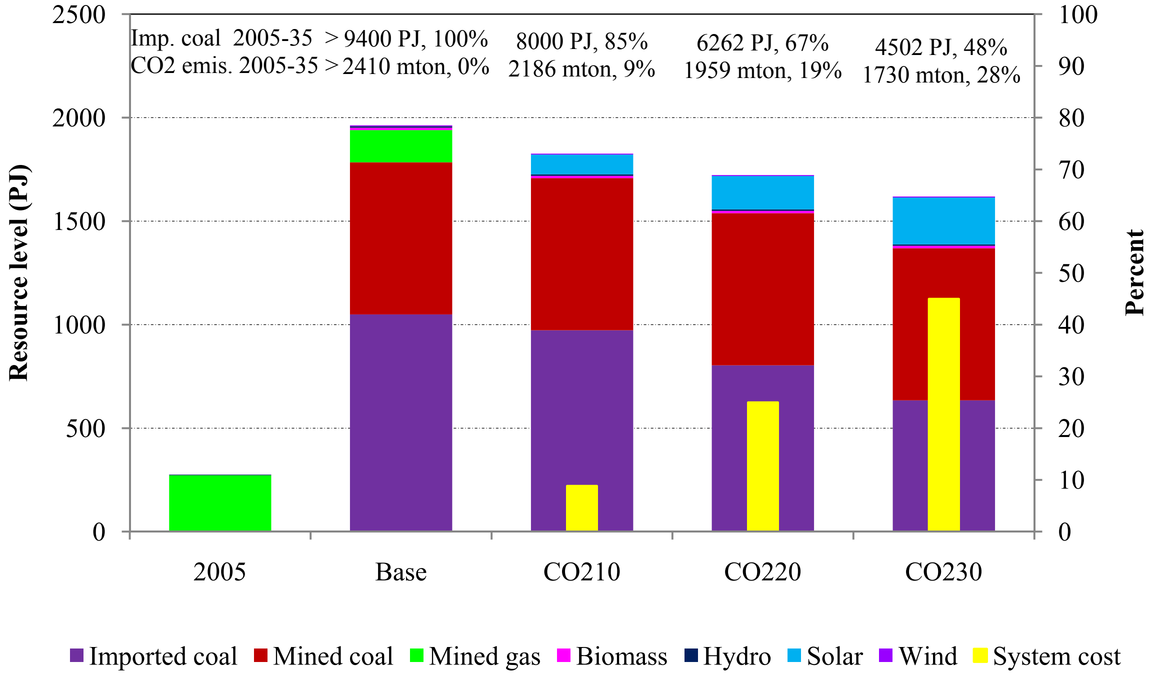

Figure 6.9: CO_2 emission reduction targets compared to base scenarios. Primary energy mix in 2035 and percentage change in cumulative (2005 - 2035) system costs. Also indicated are the energy mix in 2005, the cumulative total and percentage imported coal, and the total CO_2 emission reduction (2005 - 2035)

A reduction in the total primary energy requirement is another co-benefit of the CO_2 emission reduction targets. It is revealed that the total primary energy supply reduces by about 5.5 %, 10.4 % and 15.2 % in the CO210, CO220 and CO230 scenarios, respectively, during 2005 - 2035 as compared to the total primary energy supply in the base scenario due to efficient technology selection by the model. In the base scenario, primary energy use in 2035 is expected to be 2002 PJ, and reduces to 1658 PJ in the CO230 scenario. Gas is the dominant energy source in 2005, and coal is dominant in all scenarios in 2035. The maximum upper limit of mined coal (735 PJ) and 1050 PJ of imported coal is used in the base scenario in 2035 due to the constraint applied on the gas resource, which is based on its total availability. Coal imports decrease from 1049 PJ in the base scenario to 973 PJ, 804 PJ and 634 PJ (7 %, 23 % and 40 %) in the CO210, CO220 and CO230 scenarios in 2035, respectively. Solar energy use increases by 96 PJ, 161 PJ amd 227 PJ in 2035 in the CO210, CO220 and CO230 scenarios, respectively.

The analysis results reveal that a cumulative CO_2 emission in the entire energy system in the base scenario is approximately 2410 million tons between 2005 and 2035 (Figure 6.9). It reaches 18.25 million tons in 2010 and is expected to increase to 160 million tons in 2035. The cumulative CO_2 emission reduces by 9 %, 19 % and 28 % between 2005 and 2035 in the CO210, CO220 and CO230 scenarios, respectively.

The results show that the least cost strategy to attain the CO_2 emission reduction targets also generates benefits in the form of lower cumulative SO_2 emission during the planning horizon by 12 %, 26 % and 40 % in the CO210, CO220 and CO230 scenarios, respectively, as compared to the base scenario. The cumulative NO_2 emission during 2005 – 2035 decreases by 10 %, 21 % and 31 % in the CO210, CO220 and CO230 scenarios, respectively.

Furthermore, the results show that the increase in total system costs for reduction of cumulative CO_2 emissions over the study period is around 1910 Taka/ton in the CO230 scenario and 1600 Taka/ton in the CO220 scenario. This reduces to about 1140 Taka/ton in the CO210 scenario. These costs are much lower than those in developed countries, as the renewable-energy-based power generation is relatively much cheaper in Bangladesh.

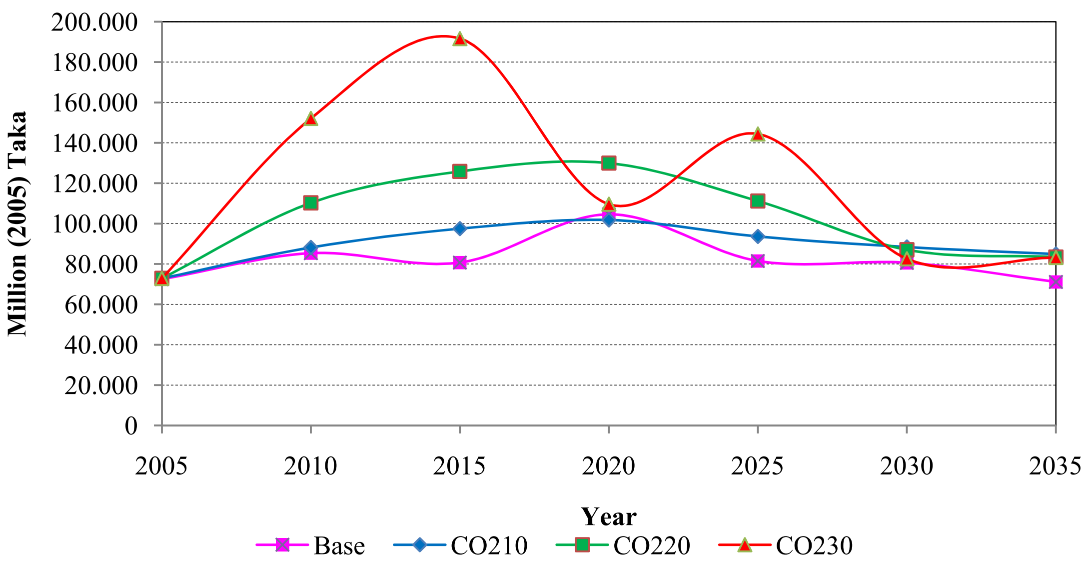

Figure 6.10: Total energy system cost in million Taka by year in the base and all CO2 emission reduction targets

Carbon tax scenarios

To summarize the results generated for each different tax scenario by the MARKAL-Bangladesh model, the power generation capacity mix in 2035 is selected as the principal metric (Figure 6.11). This provides a good indication of the types of technology choices made by the model to meet the various carbon taxes applied. Figure 6.11 shows a summary of the scenarios using the set of energy-supply technologies. The colored bars (except yellow) give the breakdown of generation capacity (GW) by technology. The numbers above each bar indicate the total and percentage of coal and oil that is imported compared to base scenario and the total cumulative electricity genaration from coal-based power plants and renewable technologies (expressed in TWh). The center yellow bar in the four scenarios on the right in this figure shows the change in cumulative total system cost relative to the base scenario. Due to the large uncertainties in this kind of analysis, it uses the percentage change in system costs between the various scenarios as the measure of the cost impact of the chnages imposed by each scenario. The system costs for the base scenario is the reference costs in all costs comparisons.

The power generation capacity level in 2035 varies from 95 GW to 99 GW in the medium, medium-high and high tax scenarios, i.e., is roughly double the 2035 capacity level in the base and low-tax scenarios. Capacity increases about 10-fold in the base and low-tax scenarios compared to 2005. Capacity levels of coal conventional, hydro and wind are not changed during the study period. Gas-based simple cycle, steam turbine and biomass-based power plant capacity levels slightly decrease when taxes increase. The model reveals that advanced coal FGD plants are less costly in 2015 in the low and medium tax scenarios. Solar PV capacity increases to a maximum of 41.63 GW in 2035 in the medium-high and high tax scenarios.

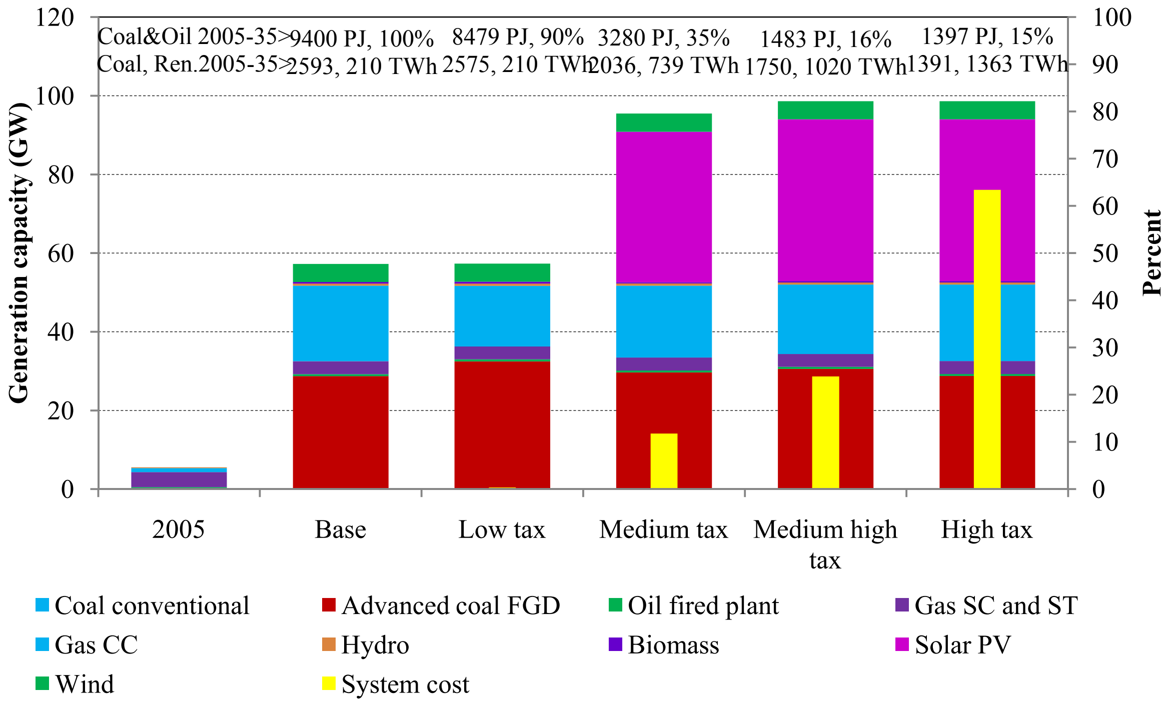

Figure 6.11: Carbon tax scenarios. Power generation capacity in GW in 2035 and change in cumulative (2005-2035) system costs in percent. Also indicated are the generation capacity in 2005, the cumulative total and percentage imported fuels, and the total electricity genaration from coal and renewable energy between 2005 and 2035 (SC = simple cycle, ST = steam turbine, FGD = flue gas desulphurization, CC = combined cycle, PP = power plant, PV = photovoltaic)

Clean technologies such as solar PV and efficient technologies such as advanced coal combustion with FGD, and gas-based combined cycle power plants are selected in place of less costly ones, thus enabling reductions in coal imports (in 2005 oil imports were only about 3.6 PJ in the medium-high and high tax scenarios) between 2005 and 2035 compared to the base scenario import level of 9400 PJ in all tax scenarios. The low tax scenario allows a reduction in imported coal use of about 10 %, contributing only 0.34 % increase in system costs during 2005-2035. Import dependency reduces by 65 %, 84 % and 85 % in the medium, medium-high and high tax scenarios, respectively compared to the base scenario, but contributes to increase in the total system costs of 12 %, 24 % and 63 %, respectively. Alternatively, import dependency based on the base scenario value of 100 % drops to 90 %, 35 %, 16 % and 15 % across the lower to higher tax scenarios, repectively.

A cumulative total electricity generation of 3646 TWh is required to meet the entire energy demand. Electricity generation from gas-based power plants increases from 841 TWh in the base scenario to 892 TWh in the high tax scenario between 2005 and 2035. Coal-based generation decreases from 2593 TWh in the base scenario to 2036 TWh, 1750 TWh and 1391 TWh in the medium, medium-high and high tax scenarios, respectively, during the study period. On the other hand, generation from renewable technologies increases from 210 TWh (5.8 %) in the base scenario to 739 TWh (20.3 %), 1020 TWh (28 %) and 1363 TWh (37.4 %) in the medium to high tax scenarios, consecutively between 2005 and 2035.

A cumulative CO_2 emission is 2410 million tons in the base scenario and it falls slightly in the low tax scenario. To achieve greater reduction in CO_2 emission, carbon tax is needed to increase. A cumulative CO_2 emission decreases by 22 %, 32 % and 42 % in the medium, medium-high and high tax scenarios, respectively, compared to base scenario.

The emission in the low tax and high tax scenarios significantly differ in the entire study period, but when the tax levels are between low and high, the emission reduction trends are also more or less similar (Figure 6.12). In the low tax scenario, there is no considerable reduction of emissions, as the choices of technologies do not change much. Further tax increases show a gradual reduction in emissions, while the medium and medium-high tax scenarios show the strongest reduction after 2020. In the high tax scenario, the CO_2 emission reduction is almost same after 2020 and varies between 42 % and 49 % between 2020 and 2035. Emission reduction reduces in the later periods due to higher renewable-energy-based power generation (mainly solar PV).

Carbon tax and solar PV generation costs can compete with fossil-based power generation in the later periods. However, due to an increased demand in the future, there is no choice but to use fossil-fuel-based technologies, as solar PV technology cannot cater to the entire demand. That is why the model reveals almost the same level of CO_2 emission reduction about 71 million tons (54 %) to 74 million tons (56 %) in all tax scenarios in 2035 except low tax scenario where the emission slightly increases compared to base scenario. It clearly shows that higher tax reduces maximum 49 % in 2030 over base scenario CO_2 emission and not more than that in the later periods. In low tax scenario in 2015 and 2035, and medium tax scenario in 2015, the model finds a least cost solution with emitting higher level of CO_2 over the base scenario. The mitigation of CO_2 in the early periods is less than in the later periods due to the fact that the model makes choices in energy use and technology investment and deployment in early years that have consequences for later periods. It also shows that there is room to deployment of renewable technologies in the later periods at a certain level.

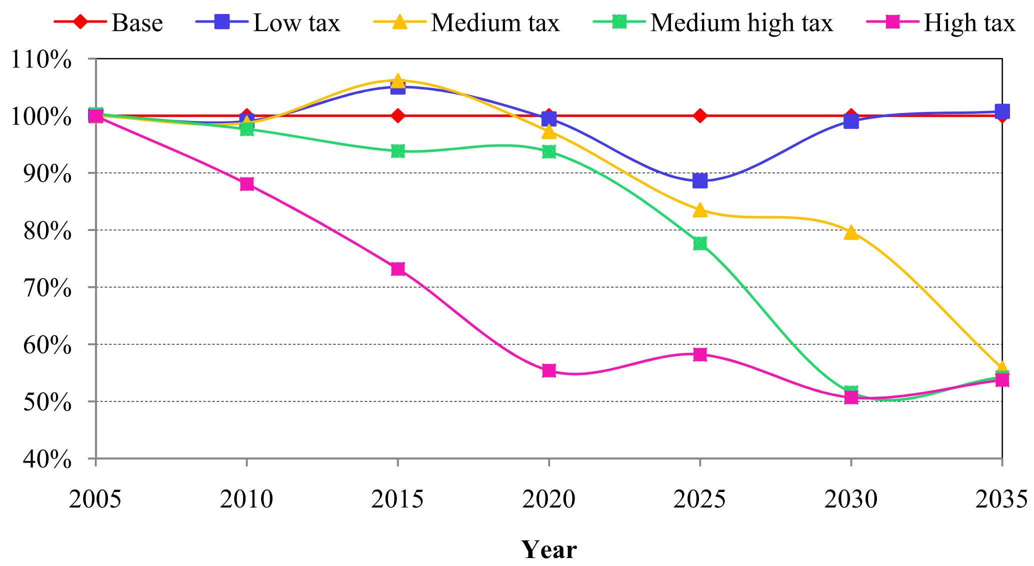

Figure 6.12: CO_2 emission reduction by percent and year in the base and all tax scenarios

7 SUMMARY AND CONCLUSIONS

7.1 Summary methodology

This study aimed at providing decision support for optimizing the long-term power supply in Bangladesh with a special focus on renewable energy technologies. To fulfill this broad objective, the MARKAL model was selected and adapted to the Bangladesh power sector. As MARKAL requires exogenous electricity demand, the LEAP model was used to calculate the future demand for different sectors of the economy. The following methodologies were applied:

1) Assessment of the potential of renewable energy resources for power generation: Renewable energy sources such as sun and wind are widely available but renewable energy does not exist in ready-to-use forms for power generation. The theoretical potential of renewable energy resources is relatively high. However, in the course of exploitation, constraints such as land use, geographical area and climate are encountered. To make use of these resources, suitable sites need to be identified, which also must guarantee minimum disturbance to the surroundings. In the case of wind power, these conditions mean that wind turbines should be located within a certain distance from residential areas to reduce noise and shadow effects. In the case of solar photovoltaic (PV), however, these constraints do not apply because this technology causes almost no noise or pollution. Therefore, different methodologies need to be developed for each renewable-energy-based power generation.

2) Projection of long-term electricity demand: MARKAL is a demand-driven model. The energy demand is driven by the availability of technologies and primary energy resources that can be exploited. Therefore, using the LEAP model, the electricity demand was forecasted in as much detail as possible. The model was used to develop different electrical demand projections based on different GDP growth scenarios, as the relationship between energy consumption and economic growth is widely documented in the energy economics literature. The scenarios in LEAP were generated to encompass all factors anticipated to change over time.

3) Development of the MARKAL-Bangladesh model: The exogenous parameters of power generation used for the development of the MARKAL-Bangladesh model can be grouped in three broad categories, namely i) power or energy demand, ii) availability of energy resources, and iii) conversion technologies. Issues like market price of power, fuel prices, etc., although individually important, are linked in this study with any one or with a combination of the above categories. Modeling with MARKAL requires establishment of relationships between technologies, activities and energy flows. The Bangladesh power sector was taken as the reference energy system and represents the activities and technologies in an energy system. It depicts energy demand, energy conversion technologies, fuel mixes, and the resources required to satisfy the energy demand.

4) Modeling the Bangladesh power sector with special focus on renewable energy technologies: Like other economic scale models, the MARKAL model was originally designed and applied in developed economies at a time when renewable energies accounted for only a small share of the overall energy use, and when environmental problems were not of serious concern. Therefore, the renewable energy technologies do not represent the central focus of MARKAL, and there are no separate functions to handle renewable energy technologies in the model. Nevertheless, the model provides several parameters that can be applied to specify the existence of these technologies. The overall approach is that first characteristic of technologies are indentified, and then possible parameters are looked at to take these features into account.

5) Scenario development: In the MARKAL model, several scenarios were developed to determine future power supply options in Bangladesh. The effects of the introduction of CO_2 emission reduction targets and carbon taxes were also modeled to determine the consequential change in the structure of the power supply sector and to assess the potential reduction in CO_2 emissions.

7.2 Interpretation of results

Potential of renewable energy for power generation

The results of this study reveal that Bangladesh has a good potential of renewable energy resources for power generation. Based on the four investigated resources, i.e., solar, wind, biomass and hydro energy, solar energy appears to be the most promising because i) the technical potential of solar PV is high (50174 MW), and ii) solar PV technologies are experiencing great improvements in technologies and cost reduction. The potential of wind, biomass and small-hydro is estimated at 4614 MW, 566 MW and 125 MW, respectively.

Electricity demand

Total electricity consumption was 17.7 TWh in 2005 and is projected to increase 7.7 times to 131.6 TWh by 2035 in the low GDP growth scenario. In the average and high GDP growth scenarios, the demand in 2035 shows an increase that is about 11 and 16 times the 2005 value, respectively. The per capita electricity consumption increases from 128 kWh in 2005 to 658 kWh, 963 kWh and 1451 kWh in 2035 in the low, average and high GDP growth scenario, respectively. The consumption of electricity in the residential sector increases significantly, as almost the entire country is projected to be connected to the electricity network by 2035. In the average GDP growth scenario, the total residential sector consumption was 7.7 TWh in 2005 and is projected to increase about 8-fold to 64.5 TWh. In the industrial sector, electricity consumption is projected to increase about 14-fold by 2035. The agricultural sector demand also increases significantly over the analysis period. In 2005, total consumption was only 0.9 TWh and increases about 11.4 times by 2035.

Base scenario

1) The total electricity generation capacity is expected to increase from 10.6 GW in 2010 to 57.3 GW in 2035, i.e., at an average growth rate of 7 %.
2) The share of gas-based power plants reduces from 90 % (9.6 GW) in 2010 to 39 % (22.5 GW) in 2035 in total capacity, whereas the increase in the share of coal-based power plants from 2.3 % (0.3 GW) in 2010 to 50 % (28.7 GW) in 2035 is extremely high.

3) The switch from gas- to coal-based power plants leads to a strong increase in coal consumption of 3.3 PJ in 2010 to 1784.3 PJ in 2035, i.e., at an average growth rate of 28.7 %.

4) The proportion of imported coal in the total fuel consumption would increase substantially from 18 % (208.4 PJ) in 2025 to 54 % (1049.3 PJ) in 2035.

5) The model predicts that electricity production is dominated by power plants based on advanced coal steam with flue gas desulphurization (FGD). These produce electricity amounting to 24 % (14 TWh) of the total power generation in 2015 and 84 % (189 TWh) in 2035.

6) The share of renewable energy technologies in overall capacity increases from 4.13 % in 2005 to 9.71 % in 2035.

7) The cumulative CO_2 emission from the entire energy system is approximately 2410 million tons between 2005 and 2035. It reaches 18.25 million tons in 2010 and is expected to increase to 160 million tons in 2035.

Cost minimization scenarios

1) Advanced coal FGD plants are the best choice among all fossil-fuel-based technologies.

2) In the renewable target production and null coal import scenarios, solar PV plays an important role in the generation of electricity, and the capacity is expected to grow by 14.2 GW and 40.8 GW, respectively, by 2035. Other renewable energies reach their allowed maximum capacity levels in these scenarios.

3) The technology learning cost for solar PV enhances competitiveness of the technologies and lead to a higher rate of implementation of solar PV in the analysis period.

4) The renewable target production scenario shows a 2.4 times higher renewable energy production capacity by 2015, about 4 times by 2025 and about 3.6 times by 2035. However, in the coal scenario, there is a much higher degree of renewable technologies implementation with a more than 8-fold capacity increase in 2035 over the base scenario 2005.

5) The limited gas, renewable target production and null coal import scenarios reduce the overall energy system CO_2 emissions by 28 million tons, 300 million

tons and 644 million tons between 2005 and 2035, respectively compared to the base scenario.

6) The total system costs rise by an overall percentage increase of 1 %, 13 % and 24 % in the limited gas, renewable target production and null coal import scenarios, respectively compared to the base scenario.

CO_2 emission reduction scenarios

1) The introduction of CO_2 emission reduction targets directly affects the shift of technologies from high carbon content to low carbon content fossil-based and clean renewable energy-based technologies. The total power generation capacity is expected to increase from 10.6 GW in 2010 to 84.7 GW, 92.6 GW and 101.5 GW in 2035 in the 10% CO_2 emission reduction (CO210), 20% CO_2 emission reduction (CO220) and 30% CO_2 emission reduction (CO230) scenarios, respectively.

2) The model reveals that the least-cost solution is to use the limited gas reserves in the short-term period, although the gas-based combined cycle plants are mostly unused in the long-term period (2025 - 2035). That is why the power generation capacity based on coal FGD increases significantly in this period.

3) The capacity share of renewable technologies in total power generation rises by 20%, 29% and 35% in 2035 in the CO210, CO220 and CO230 scenarios, respectively. In these scenarios, 12.7 GW, 21.4 GW and 30.1 GW solar-PV-based generation capacities, respectively, are additionally selected.

4) The cumulative net energy imports 2005 - 2035 are reduced in the range of 1400 PJ to 4898 PJ compared to the base scenario. The total primary energy requirement is reduced in the range of 5.5 - 15.2 %, and the primary energy supply system is diversified compared to the base scenario.

5) The total system cost slightly rises by an overall percentage increase of 9 %, 25 % and 45 % in the CO210, CO220 and CO230 scenarios, respectively.

Carbon taxes scenarios

1) Clean technologies such as solar PV and efficient technologies such as advanced coal combustion with FGD and gas-based CC power plants are selected in place

of less costly ones, thus enabling reductions in coal imports between 2005 and 2035 compared to the base scenario import level of 9400 PJ in all tax scenarios. The low tax scenario allows a reduction in imported coal of about 10 %, contributing an only 0.3 % increase in system cost in 2005 - 2035.

2) Import dependency reduces by 65 %, 84 % and 85 % in the medium, medium-high and high tax scenarios, respectively, compared to the base scenario, but contributes to an increase in the total system costs of 12 %, 24 % and 63 %, respectively.

3) Coal-based generation decreases from 2593 TWh in the base scenario to 2036 TWh, 1750 TWh and 1391 TWh in the medium, medium-high and high tax scenarios, respectively, during the study period.

4) Generation from renewable technologies increases from 210 TWh (5.8 %) in the base scenario to 739 TWh (20.3 %), 1020 TWh (28 %) and 1363 TWh (37.4 %) in the medum to high tax scenarios between 2005 and 2035.

Robust solutions

Based on the combined analysis of normal cost minimization, CO_2 emission reduction target and carbon tax with cost minimization scenarios, it can be summarized that the accelerated development of renewable energy is the most robust solution for the Bangladesh power sector (renewable target production scenario). Dependency on fossil fuel imports decreases by 34 % compared to the base scenario, but contributes to an increase in the total system costs of 13 % in the renewable target production scenario. The primary energy supply system would diversify from a system dominated by coal in the later period (2025 - 2035) to one involving a greater use of renewable resources in the renewable target production scenario. The analysis shows that the primary energy requirement would decrease, which would enhance the country’s energy security. Furthermore, the results show that the increase in total system costs for the reduction of cumulative CO_2 emissions over the study period is around 1250 Taka/ton in the renewable target production scenario. A carbon tax could also be used for subsidies to accelerate development of renewable energy technologies, as their investment cost is relatively high.

7.3 Conclusions

The model results show that none of the existing power plants are used during the analysis period. All scenarios suggest that investment in new and efficient higher-capacity coal (coal steam with flue gas desulphurization), gas-based combined cycle and solar PV power plants are more economically viable than running the existing plants.

The results also show that the degree of diversification in the total energy requirement would increase in all alternative scenarios. The primary energy supply system would diversify from a system dominated by coal in the later period (2025 - 2035) to a system involving a greater use of renewable resources. The analysis shows the primary energy requirement would decrease in the scenarios with CO_2 emission reduction targets and carbon taxes. This would enhance the country's energy security.

The results show that the increase in total system costs for reduction of cumulative CO_2 emission over the study period is around 625 Taka/ton to 1910 Taka/ton in all alternative scenarios, except in the low tax scenario where the CO_2 emission reduction is very low. These total system costs are much lower than those in developed countries, as the renewable-energy-based power generation is relatively much cheaper in Bangladesh. This study also provides an overall picture of the renewable energy potential, and demonstrates to which extent renewable energy technologies can be integrated into the Bangladesh power sector. It could thus be attractive for developed countries (so-called Annex 1 countries in the UNFCCC) to invest in renewable energy technologies, specifically in solar PV, in Bangladesh to reduce their committed CO_2 emissions defined in the Kyoto Protocol through the clean development mechanism (CDM).

Furthermore, both targets for reduction of CO_2 emissions and carbon taxes are to be fixed with respect to the capacity of the economy to bear the extra cost of emission reduction. The cost should also be compared with other means of reducing CO_2 emissions. For example, attention should be paid to the conservation measures, such as the use of efficient end-use equipment e.g., compact fluorescent lamp (CFL), electronic ballast for lighting. These measures would lead to some additional costs but would decrease the electricity demand, and this decrease in demand would in turn lower the CO_2 emission level. These alternatives are to be weighed with respect to each other before finalization of a national energy policy for CO_2 emission reduction targets or carbon taxes.

As the solar potential is relatively very high, the mission for next 20 years should be to make Bangladesh a solar energy country. Such a national solar energy mission should be a major issue of the government of Bangladesh with the aim to promote ecologically sustainable growth while addressing the country's energy security challenge. This would also constitute a major contribution by Bangladesh to the global effort to meet the challenges of climate change.

Achieving these promising objectives will require visions, strong policy support and the recognition that the higher near-term investment costs will be paid back in the long run with significantly lower costs for imported fuels, cleaner air and reasonable energy security for Bangladesh.

Limitations of MARKAL

1) Since the economic and energy demand projections are exogenous in the standard MARKAL model, there is no feedback between the technology mix and the technology drivers. For example, a change in the technology mix toward better efficiency cannot cut total demand or change fuels prices.
2) Due to the nature of linear programming, MARKAL always chooses the least-cost solution. In that case, energy services with the lowest cost will be taken for the entire market, and the competitors with only slightly higher costs will be excluded.
3) To simulate the decisions needed for definition of the necessary energy supplies to satisfy the projected energy demand, MARKAL does not capture detailed characterictics of technologies, i.e., the hourly load profile, which is an important parameter considering the intermittent output of renewable energy technologies. This thus leads to a rough assessment of the influence of renewable energy technologies within the power generation system.
4) The MARKAL model can answer the questions: i) when to invest in new generation units, ii) what type of generation units to install, and iii) what capacity of generating units to install. However, it cannot answer the question iv) where to invest in new generating units.

Limitations of the study

One of the difficulties in this study was the availability of reliable data on the energy sector, since up to now no independent energy statistical organization has existed in Bangladesh. Therefore, the data used in this study were collected from different sources such as the Bangladesh Power Development Board, Power Cell, Ministry of Power, Energy and Mineral Resources, Petrobangla, numerous research studies, and from national and international publications. When processing these data, special attention was paid to synchronizing the data consistently. In cases where data was not readily available, the data was estimated based on internationally accessible information and data from various organizations and publications, taking into account the specific conditions in Bangladesh. Emission levels were estimated based on literature.

Some forms of renewable energy are not considered such as solar thermal, wave energy, tidal and fuel-cell energy, because their development technologies are not advanced and are not suitable for Bangladesh.

The costs of the renewable energy technologies are the main factor affecting the selection of the representative technology. The cost can be unrealistic based on dependence of technology development.

All technologies with the same input and output are presented by one representative technology in MARKAL without considering the locations.

Outlook

The standard version of the MARKAL-Bangladesh model can be used for various energy-related studies. An expansion of the model can be done using the total energy system with the MACRO model. MARKAL-MACRO merges the bottom-up engineering to top-down macro-economic approaches, adds price elasticity to energy service demand, and links changes in the energy system to the level of economic activity while maintaining the technological richness and flexibility of MARKAL.

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