Development of a modified dynamic energy and greenhouse gas reduction planning approach through the case of Indian power sector

Dissertation

Zur Erlangung des akademischen Grades

Doktor-Ingenieur

vorgelegt am

Fachbereich 12

Maschinenwesen-Energietechnik-Verfahrenstechnik

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Jyotirmay Mathur
aus Indien

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Jyotirmay Mathur

Zusammenfassung

Die Methodik der Bilanzierung des kumulierten Energieaufwandes hilft bei der Betrachtung der umweltrelevanten Auswirkungen von Energiesystemen. Dabei werden alle Energieaufwendungen und die daraus resultierenden Emissionen während des gesamten Lebensweges von der Herstellung eines ökonomischen Gutes über die Nutzung bis zur Entsorgung, bilanziert. Das Verhältnis zwischen dem Kumulierten Energieaufwand bzw. den Kumulierten Emissionen und der Energiebereitstellung durch das betrachtete System stellt anhand Kenngrößen wie „Erntefaktoren“ und „Emissionskoeffizienten“ ein Maß für die ökologische Verträglichkeit dar. Eine weitere Vorgehensweise der Analyse der ökologischen Verträglichkeit ist die klassische Energie- und Umweltplanung. Diese Methode analysiert die definierte Fragestellung aus dem Blickwinkel einer makroskopischen Betrachtungsweise. Hierzu wird ein definiertes Referenzenergiesystem, in seiner Entwicklung unter vorgegebenen Randbedingungen und variabler Auslegung der Betrachtungskriterien, hinsichtlich möglichst geringer Systemkosten optimiert.

Um diese beiden Herangehensweisen zu verbinden, wird eine weiterentwickelte Methodik eingeführt. Dies geschieht durch die Verbindung des Kumulierten Energieaufwandes (ein systemspezifischer, statischer Parameter) mit der Entwicklung des Energiebedarfs des betrachteten Referenzsystems. Die Entwicklung des Energiebedarfs ist hier insbesondere ein dynamischer Parameter der durch seine Wachstumsrate bestimmt wird. In dieser Methodik verhält sich der Kumulierte Energieaufwand wie eine Barriere für das Wachstum, da durch ihn Energie aus dem gesamten Energiedargebot gebunden wird. Der Wert der maximalen Wachstumsrate wird dadurch ermittelt, dass das Ergebnis der Gleichgewichtsbeziehungen der verschiedenen Techniken dem Energieplanungswerkzeug zugeführt wird. In der vorliegende Arbeit werden die Methoden beispielhaft anhand verschiedener Energieanlagen dargestellt. Dazu wird die weit verbreitete Planungssoftware MARKAL (MARket Allocation) verwendet. Diese Software betrachtet das definierte Referenzsystem als dynamisches Problem und löst es nach möglichst niedrigen Systemkosten durch die Bestimmung eines unvollständigen Gleichgewichtes aller Zwischenschritte.

Durch die Betrachtung der indischen Elektrizitätsversorgung wird diese Methodik an einem konkreten Anwendungsfall getestet. Die Kraftwerkskapazität in Indien wuchs in der Vergangenheit nicht ausreichend genug, so dass sich eine stetige Verknappung der Elektrizitätsversorgung einstellte. Hinzu kommt, dass die Notwendigkeit der Kontrolle des Treibhausgasausstoßes wächst. Aus diesem Grunde werden in dem Modell der indischen Energieversorgung mehrere Szenarien aufgestellt, um die wichtigsten zukünftig denkbaren Möglichkeiten abzudecken. Die Einflüsse und Effekte von unterschiedlich hohen CO_2-Steuern –ein von der Indischen Regierung angestrebtes Steuerungsinstrument- wurden ebenfalls mittels der beschriebenen Methodik modelliert. Zum einen soll somit die Veränderung der Struktur einer zukünftigen Elektrizitätsversorgung ermittelt und zum anderen mögliche Emissionsminderungen an- und aufgezeigt werden.

Die Ergebnisse dieser Studie weisen darauf hin, dass die CO_2-Emissionen um bis zu 25% reduziert werden könnten. Abhängig von dem erreichbaren Reduzierungsziel, ergeben sich CO_2- Vermeidungs bzw. Reduktionskosten in Höhe von 100 bis 140 indische Rupien/t CO_2 dies entsprechen rund 2,5 €/t CO_2 bis 3,5 €/t CO_2. Im Vergleich zu deutschen Verhältnissen fallen diese Aufwendungen in Indien deutlich geringer aus, da z.B. die Nutzung erneuerbarer Energien in Indien ökonomischer ist. Des weiteren wird in allen Ergebnissen der unterschiedlichen Szenarien gezeigt, dass ein forcierter Ausbau von großen Wasserkraftwerken und der verstärkten Nutzung der Windenergie, aufgrund einer besseren Wirtschaftlichkeit gegenüber den Bedingungen in Deutschland, vorteilhaft ist. Weiterhin besteht in Indien die

Möglichkeit, erdgasbefeuerte Kraftwerke den vorhandenen Kohlekraftwerke vorzuziehen, gegenwärtig jedoch sind druckaufgeladene, kohlebefeuerten Wirbelschichtfeuerungsanlagen, wenn sie zur Verfügung ständen, energetisch und emissionsseitig günstiger. Ein weiteres Ergebnis ist, dass fortschrittliche Techniken -wie IGCC und Photovoltaik-Kraftwerke- oder erdölbefeuerte Kraftwerke aufgrund ihrer derzeitigen Kostenstruktur und Betriebskriterien in keinem der untersuchten Szenarien rechnerisch in Lösung gehen.

ABSTRACT

Energy and Environmental Analysis is a method to evaluate utility of any energy system by finding the requirement of energy and resulting emissions through all the materials and processes used to build and use any system over its entire life and also to demolish it at the end of life. Relationship between the cumulative energy demand and cumulative emissions with energy output from the system establishes indicators for its utility in terms “Energy Yield Ratio” and “Emission Coefficient”.

Energy and Environmental Planning is a macroscopic exercise used for conducting futuristic studies through dynamic assessment of the defined reference energy system comprising of many alternatives and constraints. It is done to find the optimum solution for certain objective function often system cost minimization through meeting system requirements such as the energy demand.

To establish link between these two approaches, a new methodology has been formulated in this work. It has been done through linking the Cumulative Energy Demand (a system specific, energy analysis parameter of static nature), and the overall energy demand which is a dynamic parameter governed by its rate of growth. With the help of this new method, Cumulative Energy Demand of any system acts as a barrier for growth as it takes away energy from the overall energy pool. The value of maximum growth obtained through equilibrium equations has been exogenously supplied to the energy planning tool and thus the link between the two different approaches has been established. This work demonstrates the method for each of the above approaches separately and then jointly, involving various technologies for power generation. A much widely used energy planning software MARKAL (MARket ALlocation), has been used for carrying out planning related analysis which treats the defined Reference Energy System as a dynamic bottom-up problem and finds the objective function through obtaining a partial equilibrium at all intermediate stages. The above mentioned methodology has been validated through the analysis of Indian power sector. There has been an unsatisfactory growth in this sector during past few years which has resulted into increase in the shortage of power supply. Besides, pressure for controlling the emission of greenhouse gases is increasing day by day. Therefore, model of the Indian power sector has been developed and several scenarios have been made to cover various major possibilities for the future. Effects of introduction of CO_2 taxes at different rates have also been modeled through the developed approach to find the consequential change in the structure of power sector and to assess the potential for reduction in emissions.

Results obtained indicate that during the period up to the year 2025, there exists a possibility of reducing carbon dioxide emissions up to about 25%. The system will incur about 100 to 140 rupees (approximately 2.5 to 3.5 Euro) for reduction of each ton of carbon dioxide depending upon the target and hence decided emission tax rates. These costs are much less as compared to the rates found for other countries like Germany, as the renewable energy based power generation is relatively much cheaper in India. It has also been found that it would be better to pay more attention towards large hydro and wind power as they tend to be more economic in almost all scenarios. There also exists a possibility for natural gas based power plants to replace coal based plants but at present Pressurized Fluidized Bed Combustion based coal power plants would be better. As one of the results it is also inferred that advanced technologies like Integrated Gasification Combined Cycle based coal power plants, oil based power plants and photovoltaic power plants are not competitive enough with their present cost and performance criteria, in any of the considered scenarios.

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ABBREVIATIONS AND NOMENCLATURE USED

Abbreviations

AFBC	Atmospheric Fluidised Bed Combustion
APM	Administered Price Mechanism
CCGT	Combined Cycle Gas Turbines
CED	Cumulative Energy Demand
CEL	Central Electronics Limited, India
CGHE	Cumulative Green House Gas Emissions
CH_4	Methane
CO_2	Carbon dioxide
CON	Energy Conversion technology
CV	Calorific value
DMD	Demand Technology
ECN	Netherlands Energy Research Foundation, Netherlands
EDM	Energy Demand (used in dynamic energy analysis)
EEA	Energy and Environmental Analysis
EFS	Fossil Fuel
EHC	High Temperature Cooling/Heating (as energy carrier)
ELC	Electricity
ENC	Energy Carriers (Standard)
ENT	Energy Carrier's Table
ENU	Nuclear Fuel
ERN	Renewable Energy Source
ESY	Synthetic Fuel
FOS	Fossil fuel based Technology
GDP	Gross Domestic Product
GERAD	The Group for Research in Decision Analysis, Canada
GHG	Greenhouse Gases
HSD	High Speed Diesel
IFIAS	International Federation of Institutes for Advanced Studies, Sweden
IGCC	Integrated Gasification Combined Cycle
IIM	Indian Institute of Management, India
IPCC	Intergovernmental Panel for Climate Change
LHV	Lower Heat Value
LPG	Liquefied Petroleum Gas
LSHS	Low Sulphur Heavy Stock
LTH	Low Temperature Heat
MTOE	Million Ton Oil Equivalent
NO_x	Oxides of nitrogen
NST	Night Storage System

O&M	Operation and maintenance
PFBC	Pressurised Fluidised Bed Combustion
PRC	Energy Production Technology
REN	Renewable Energy Based Technology
RES	Reference Energy System
SO_2	Sulphur dioxide
STG	Energy Storage Technology
T&D	Transmission and Distribution
TCH	Technology
TDSC	Total Discounted System Cost
U_{233}	$Uranium_{233}$
UHV	Upper Heat Value

Short forms of units

GJ	Giga joule
kJ	Kilo Joule
km.	Kilometre
kWh	Kilo Watt Hour
lt.	Litre
m.	Metre
MJ	Mega Joule
MWh	Mega Watt Hour
PJ	Peta Joule
TJ	Tera joule
TWh	Tera Watt Hour

Suffixes used in equations

c	Construction
d	Disposal
d	Type of energy demand
el	Electrical
f	Form of energy
i	Form of energy import/export
k	Type of technology
p	Production
P	Peak
prim.	Primary
t	Time
u	Utilisation

Chapter-1

INTRODUCTION OF THE PROBLEM

1.1 Energy-Environment-Resource Linkages

There is an almost unanimous agreement world-wide that activities in developing countries specially in China and India are going to play a major role in deciding the fate of energy and environmental issues of global concern. Aggregate energy consumption in the developing countries is not far less than the developed countries which is likely to increase only in near future. Increasing energy consumption not only results in depletion of energy resources but also gives rise to problems like global warming and greenhouse effect through emissions generated by burning of fossil fuels. Table 1.1 shows energy consumption in developing and developed countries in the year 1995. Emissions in world's top 12 countries in which some developing countries including India have also figured out along with major developed countries are shown in table 1.2.

Table 1.1: Energy consumption in developing and developed countries of the world

Region	Commercial Energy (PJ)	Traditional Energy (PJ)	Total Energy Consumption (PJ)
Developing Countries	**134569**	**19068**	**153637**
Central & South America	18823	3533	22356
Asia	106770	10308	117078
Africa	8976	5227	14203
Developed Countries	**234382**	**5897**	**240279**

Source: [Bansal 2000]

1.1.1 Co-relation Between Energy and Environment

Out of the world-wide total energy consumption of 365 EJ (364,891 PJ) in the year 1995, 90% of energy was supplied by burning fossil fuels. Studies have shown a strong co-relation between energy consumption and environmental degradation due to this large dependence on fossil fuels. In the same year a total of 22.71 billion tonnes of CO_2 emissions were generated world-wide out of which more than 80% were due to energy related activities only [WRI 1999]. Over past fifty years, per capita energy consumption in India has increased at an average rate of about 100% per decade and per capita greenhouse gas emission has increased in tune with it. However, these figures for India are much lower as compared to the corresponding figures for developed countries. In the U.S., per capita energy consumption was 326.3 GJ per annum and greenhouse gas emission was 20.8 tonnes CO_2 per annum. As compared to these values, per capita figures of just 13 GJ per annum and nearly one tonne CO_2 emission per annum has been in case of India. This gives a very serious forecasting that if no corrective measure is taken, due to developmental activities and improvement in quality of life, the per capita energy consumption and emission in developing countries will rise continuously for next few decades.

This will not only make these figures of developing countries touch the aggregate figures of developed countries but also increase the global energy consumption and greenhouse effect drastically.

Table 1.2: World's dirty dozen countries (top twelve CO_2 emitters)

Country	Annual primary energy consumption (PJ/a)	CO_2 emission (million tonnes/a)
Canada	9404	435.7
China	34310	3192.5
Germany	13511	835.1
India	10513	908.7
Italy	6906	410.0
Japan	18711	1126.8
Korea	5451	373.6
Maxico	5473	357.8
Russian Fed.	29444	1818.0
U.K.	9080	542.1
Ukraine	6985	438.2
USA	8844	5468.6

Source: [Bansal 2000]

1.1.2 The Resource Crunch

Over the past few decades, world-wide and so in India, a decline in precious fuel reserves has been observed. Although, some new reserves have been explored and few more are expected to be added to the known reserves, estimates have shown that except coal, fossil fuel reserves are going to last not even till the middle of this century. The new reserves are also not expected to offer an economic extraction/excavation as compared to prevailing costs today. Moreover, threat of depleting fuel reserves has given new directions to international politics which influences the availability and costs of fuels as happened in 1974 at the time of Gulf-Crisis. Therefore, during the past few years, special thrust has been given to decrease dependence on fossil fuel resources by harnessing renewable energy options that except for wind and hydro power, are not very cost economic. In India, and similarly in other developing countries, availability of limited funds is also considered as another resource constraint that are to be most judiciously utilised for growth. This situation demands need of an optimised approach for resource preservation and promotion of renewable energy based systems for getting long term benefits.

1.2 Indian Energy Scenario

The India energy scenario is characterised by increasing consumption of fossil fuels. One typical feature of it is a large share of bio-mass based energy in the form of wood, dung-cakes etc. continuing to contribute about 30% of the gross energy consumption in the country. Consequently, gross energy consumption in the year 1995 was 13587 PJ with 908.7 million tonnes of total carbon dioxide emission. It is projected that if the prevailing growth continues, annual energy consumption and corresponding CO_2 emissions in India will grow up to a level of 35482 PJ and 2500 million tonnes by the year 2020 [Bansal 2000]. This situation is likely to arise specially due to absence of development and utilisation of proper planning tool for rationalising between cost, development and environmental problems. Therefore, in such a scenario, there is an urgent requirement of developing adequate analytical tools that on one hand can assess energy consumed in installation and operation of energy systems as well as facilitate corresponding energy and environmental analysis of power plants covering their entire life cycles. In order to long term effects, it is most necessary to do such an analysis by generating transient scenarios for demand and corresponding requirement energy sources under various constraints of availability, cost and pollution. The present thesis is one of the first efforts in this direction and it concentrates on the power sector only as it has become one of the most critical sectors in entire Indian economy acting as one major bottleneck for development.

1.2.1 The Power Crisis

There has been a perpetual shortage of electricity in India. Many reasons can be given to this power shortage. Over past 10 years, the demand of electricity has grown at an average rate of 6.13% per year compared to the supply growth rate of nearly 5%. Capacity expansion over this period has been only 4.17%. Transmission & distribution losses have increased from 20% at the beginning of previous decade to 23% in the year 1999-2000, causing extra shortage in power supply. In many states, agricultural consumption of electricity is not charged at all and in remaining, a highly subsidised rate is charged. This has encouraged inefficient utilisation of electricity in this sector again leading to disproportionate increase in energy demand. On the other hand, there has also been a change in the power demand pattern due to fuel substitution and increasing urbanisation of population. The peak demand has gone much above the average demand causing peak shortages of about 18-20% as compared to 8-10% average shortage of electricity in 1999-2000. To add to these, some ambitious power projects like 'Narmada Valley Hydro Power Project' and 'Sardar Sarovar Hydro Power Project' have been struck-up for a long time due to different political or regional issues like environmental impacts, rehabilitation etc.. In case of some other projects like 'Dhabol Thermal Power Project', unclear political priorities and policies concerning purchase of power from generation plant had forced the project to come to a standstill in an intermediate stage. These factors have not only resulted into overshooting project costs but also these are creating a barrier for private parties who want to invest in the Indian power sector. While anticipating private investments, government has already started decreasing its annual budget for expansion of power generation capacity. These effects jointly have made the power crisis in the country much more grim over past few years. In nutshell, lack of co-ordinated efforts due to absence of proper planning is prevailing in the power sector.

1.2.2 Additional Factors for Imbalance in Power Demand and Supply

Energy use has always been linked with economical activities world wide. Indian economy has undergone structural change over the last decade. As a result the annual GDP growth rate during the

Eighth Five-Year Plan (1992-97) has been 6.8% and is now expected to increase further in future. Growth of population, specially growth of urban population is another factor that drives the growth of energy demand are. During past 50 years, India's population grew at an average rate of about 2% per year. Over past 10 years, the percentage of electrified villages has increased from 83% to 87%, out of the total 579132 villages in India. Due to increased extent of electrification and growth in per capita average income in semi-rural and urban areas, fuel-substitution has taken place and in the last decade an increase of 62% has been observed in the total number of electric household goods. The cumulative effect of the above phenomenon has been the rapid increase of gross electricity demand and an ever existing shortage of supply. Typically, in India, therefore, in addition to cost, availability considerations have also become quite important [CMIE 2000]. In few states power plants are very poorly managed, running at a plant load factor as low as 15%. Such factors create an extra shortage of electricity supply despite possessing a relatively better capability of power supply.

1.3 Energy Planning and its need

1.3.1 Present Scene of Energy Planning in India

Many departments, organisations and ministries in India vested with different functions related to power generation are functional as shown in appendix-1. However, the forums and structures for co-ordinated action among these bodies are not well defined. The ministry of power is concerned with perspective planning, policy formulation, processing investments for public sector projects, administration and enactment of legislation with regard to thermal and hydro power generation, transmission & distribution. Under the ministry of power, organisations like Central Electricity Authority (CEA) that advise on technical, financial and economic matters; Rural Electrification Corporation (REC) that provides financial assistance for rural electrification programmes; Power Finance Corporation (PFC) that mobilises capital from non-budgetary sources; Power Grid corporation that is responsible for all existing & future transmission projects in the central sector; Central Electricity Regulatory Commission that regulates tariff-related matters and formulation of tariff policy; are functional. Besides, each of the 29 states have a state level ministry operating in this field through similar set of organisations. In the union government, there is an independent Ministry for Non-Conventional Energy Sources that undertakes programmes for spread of renewable energy based systems. Two separate ministries namely Ministry of Coal and Ministry of Petroleum and Natural Gas are also relevant as their policies affect price and availability of fossil fuels. Planning Commission of India is the think-tank of the government for formulation of plans and policies and setting targets for developmental activities. It has one separate Power and Energy Division that deals with the plans and policy matters related to energy sector. The Ministry of Environment comes into picture through legislative requirements implemented through the Central Pollution Control Board but its involvement in the planning stage is often not significant. Moreover, the environmental concerns so far are related to emissions directly causing adverse effect on public health like carbon mono-oxide, oxides of sulphur and particulate matter. Carbon-dioxide and other emissions having global warming potential are neither covered under the legislative framework nor considered while critically analysing any power generation project. The need of co-ordinated energy planning can be assessed by the mere fact that in 8th Five Year Plan (the government plans developmental activities in this form) only 40% of the targeted expansion could be achieved and again in the 9th Five Year Plan not more than 70% is expected to be achieved.

Energy planning with embedded environmental concerns as demonstrated through this work is therefore required for optimum utilisation of available resources including funds, conservation of fossil fuel reserves and promotion of renewable energy for improving sustainability through reduction of greenhouse gas emission.

1.3.2 Energy Planning: Use for Optimising Energy Systems

Energy is one of the key prime movers of any economy. During past few years, a co-related movement of GDP and per capita energy consumption/ total energy consumption has been observed in India. As energy is an important determinant in the development of economy, its availability is almost necessary. Following aspects therefore, require focussed attention:

- Availability of capacity for power generation
- Minimisation of generation cost of electricity (grid average)
- Minimisation of consumption of depleting resources
- Demand-supply balancing

Besides, the above issues, in contemporary energy planning practices, environmental issues are gaining more and more important place specially after the Rio Summit of 1992 and release of targets for greenhouse gas reduction through Kyoto Protocol of 1998. Energy planning has now been enhanced to include:

- Reduction/control of emission of greenhouse gases
- Demand curbing through price elasticity of power demand
- Promotion of renewable energy systems
- Introduction of carbon taxes at proper time, at proper rate.

1.4 The Present Study

1.4.1 Basic Work

In this study, one of the most widely used tools for energy planning MARKAL (MARket ALlocation) has been used for conducting energy planning studies of Indian Power Sector. Various futuristic possibilities have been covered by making multiple scenarios and uncertainties have further also been covered through sensitivity analysis. Efforts have been made to find directions for expansion of the power sector and to assess need and effects of introducing new policy like carbon taxes in India.

1.4.2 Development of Advanced Methodological Approach for Energy Planning

In this work, one new methodology for linking energy planning tool MARKAL with results of Energy Analysis (a method for analysing life cycle of individual power generation systems) has been evolved. This linking helps indirect infusion of a new parameter 'Cumulative Energy Demand' in MARKAL. A dynamic mathematical model has been formulated for this linking which on the basis of the cumulative energy demand calculates the maximum allowable growth individually for all considered technologies. Values of maximum growth for each technology and for each period are supplied externally to MARKAL to act as one of the constraints. Additional requirement for using this new approach with planning tool MARKAL is information about 'Cumulative Energy Demand' for production of new plants of each technology. For this purpose 'Energy and Environmental Analysis' of few systems has also been conducted and information has also been taken from other similar studies to act as supplementary information for this work.

1.4.3 Aims and Objectives of This Study

Following were the aims of conducting this study:

- Development of a methodology for linking energy planning tools (for growth of power sector) that can consider cost-benefit analysis with results of Energy and Environmental Analysis in the form of Cumulative Energy Demand of power plants.
- To evolve methodology for Energy and Environmental Analysis of various power generating systems for finding Cumulative Energy Demand and Emission Coefficients.
- Cost-benefit analysis of Indian power sector through developing multiple futuristic scenarios.
- Assessment of greenhouse gas emissions for above generated scenarios.
- Analysis of growth of power sector in India from the point of view of cost-benefit analysis including introduction of taxes on greenhouse gas emissions at different rates.
- Analysis of growth of power sector from point of view of reduction of greenhouse gas emissions.

Following activities were undertaken in connection with the above mentioned aims:

- Formulation of a new method for linking microscopic practices like "Energy and Environmental Analysis" with macroscopic practices for "Energy & Environmental Planning" through "Dynamic Energy Analysis".
- Energy and Environmental Analysis of selected power plants in Indian context.
- Study of Indian energy sector with special focus on power generation and demand.
- Development of MARKAL-INDIA as an analytical planning tool for Indian power sector.
- Development of different futuristic scenarios for power sector covering major possibilities related to changes in constraints, cost factors, and technological development.

1.4.4 Structure of The Study

In chapter-2 of this work, review of existing tools and practices related to Energy Planning and Energy and Environmental Analysis of power generating systems has been presented. Besides, a review of use of these tools in various countries world-wide has also been presented along with coverage on relevant work done in India so far.

In chapter-3, adopted methodology has been presented. Method used for energy and environmental analysis has been explained. Mathematical explanation of the approach used by MARKAL has also been explained. In the last section of this chapter, the new logical approach of linking Energy and environmental analysis with MARKAL has been explained through mathematical formulation.

Chapter-4, presents Energy and Environmental Analysis of selected renewable and non-renewable energy based systems. Besides, having a feel of life cycle analysis of considered technologies, the main aim of this chapter is to find results of the Dynamic Energy Analysis in the form of maximum growth rates. The results of own and other considered of energy and environmental analysis in the form of Cumulative Energy Demand have been used internally as inputs for the dynamic energy analysis and related MARKAL analysis.

Chapter-5 of this work covers development of Reference Energy System for Indian power sector. Background information has also been given in this chapter, related to availability of fuels, status of considered conversion technologies, sector-wise demand of power and other major parameters that have been supplied as input to the MARKAL model. This chapter also presents explanation of the boundaries and assumptions used in this study.

In chapter-6, future scenarios have been developed that cover major futuristic possibilities in the power sector. Changes in basic parameters mentioned in chapter-5, due to individual scenario, have also been discussed in this chapter.

In chapter-7, results of the MARKAL analysis for different parts and scenarios of this study have been presented. Chapter-8 through sensitivity analysis presents probable variation in these results due to variation in parameters used in the reference case. Chapter-9 presents, conclusions drawn on the basis of this entire work.

Chapter- 2

LITERATURE REVIEW

Energy planing and Energy-Environmental Analysis are two major fields covered in this study. The former has made major scope of this work and the later though important in itself but was specifically important for finding information required to carry out analysis based on the new approach of linking dynamic energy analysis with MARKAL. Many studies have been conducted world wide in these fields Organised research in both the fields started in late 70's and early 80's, separately. Each has attracted technocrats as well as economists and different tools and practices have evolved over the time horizon that have been covered briefly in their respective sections of this chapter with comments regarding their relevance in the current study.

2.1 Energy Planning

2.1.1 Review of Tools for Energy-Environmental Planning

Energy planning though was important ever, caught serious attention only after the 'Gulf-Crisis' in the years of early 1970s. In post gulf-crisis time only, sufficient attention has been given to critical assessment of fuel reserves, rational use and conservation of energy resources, and long term energy planning. On the other hand, the famous 'Rio Earth Summit- 1992' can be practically understood to be the triggering point for almost all environmental studies. For the first time, collectively by 167 nations, serious question marks were raised on environmental degradation specially on important phenomenon like greenhouse effect and ozone layer depletion. The issue of greenhouse gas emissions caught fire after report of the Inter Governmental Panel for Climate Change (IPCC) in 1995 which concluded that anthropogenic CO_2 emissions are having discernible impact on environment. This was followed by continued discussions, debates, legislation formation and setting of targets like Kyoto Protocol Targets for reduction of greenhouse gas emission. As per estimates, aggregated energy related activities together have an 80% contribution in the total greenhouse effect, world wide [WRI 1999]. Therefore, besides separate tools for environmental studies pertaining to assessment, projection and mitigation; energy planning tools were expanded to cover the environmental aspects of power generation. Major tools & practices that have evolved over the period in the field of energy-environmental planning can be covered in the following categories Energy Supply/Demand Driven Models, Economic/Financial Factors Driven Models and Integrated Models.

Energy Supply/Demand Driven Models

Models falling under this category are either energy optimisation models or energy sector equilibrium models. The energy sector optimisation models have a detailed specification of technologies in the energy supply and demand sectors along with a number of fuel forms. All these compete for a share in meeting the exogenous demands. The sectoral coverage of these models and that of the energy sector equilibrium models is quite similar. Only difference is that, in the former category models, objective is to minimise the present value of the overall system cost of meeting the given demand to determine the equilibrium shares of various technology options. In the later, determining the equilibrium prices based on the behaviour of individual elements is the main objective. Some of such important models are:

MARKAL (The Market Allocation Model):

Unique feature of this model is that it solves the energy system as a multi-period linear program hence, is called a dynamic linear programming tool. The solution satisfies an exogenously specified set of energy demands, minimising the system discounted cost. A number of technologies compete to satisfy a particular demand and supply of energy. MARKAL has been adopted for energy and environment studies in over twenty countries. It is one of the most widely used energy models in the world. Some important variants of MARKAL are described with relatively more details, in the section 2.1.2.

EGEAS

The Electric Generation Expansion Analysis System (EGEAS) is a modular production, costing, generation expansion software package developed under Electric Power Research Institute, USA (EPRI) sponsorship for use by utility planners to evaluate integrated resource plans, independent power producers, avoided costs and plant life management programs. It also has new modules developed to specifically accommodate demand-side management options and to facilitate the development of environmental compliance plans. EGEAS develops optimum expansion plans in terms of present worth of revenue requirements and levelized average system rates. These functions can be used to stimulate a life cycle Total Resource Cost (TRC), Rate Impact Measure (RIM), or the Most Value test similar to those usually computed in a demand side management screening analysis [EPRI 2000].

BESOM and BEEAM

Brookhaven Energy Systems Optimisation Model (BESOM) was one of the early energy optimisation models developed in early seventies for energy planning in the US. Later disaggregated econometric models of the US economy were integrated with BESOM. The Brookhaven Energy Economy Assessment Model (BEEAM) comprises an energy dominated input-output representation of the economy with energy supply and demand network. It produces a set of sectoral outputs to satisfy an exogenous demand [Messner 1997].

IFFS

The International Future Forecasting System (IFFS) is the model used to forecast integrated energy markets by the US Energy Information Administration. The model consists representation of supply and demand for all the major fuels in the US, as it is a partial equilibrium model containing a large number of equations and inequalities.

LEAP

Some energy sector accounting models have a very detailed specification of energy supply with a structure to ensure consistency. The Long Range Energy Alternatives Planning (LEAP) model of this category, for instance, follows accounting approach as the solution methodology. It essentially identifies and quantifies the long term implications of energy policy alternatives. The LEAP model has been used in many studies specially UNEP sponsored carbon abatement studies. The main strength of these studies is the detailed specification of energy and environment options, while the main deficiency is weak representation of the associated economic dynamics [SEI 2000].

BRUS

The Brundtland Scenario model (BRUS) is a long term simulation model for energy demand and supply system initially developed for making the Danish Energy Plan 2000. It applies a bottom-up methodology and calculates energy consumption, emission of CO_2 and related energy systems costs including investments, operation and maintenance costs and fuel costs. The model facilitates long term analyses and has explicitly incorporated the important long term factors of the energy system, e.g. the development of energy technologies and conservation. It operates in partly static and partly dynamic mode. Major limitation of the model is that it only calculates for the years 1994, 2005 and 2030 [RISO 2000].

NEMS

The National Energy Modelling System [NEMS) was developed by the Energy Information Administration (EIA) of the Department of Energy, US, for analysing the effects of the policy options on the US electric power sector. The model simulates the energy sector using two modules- the Electric Market Module (EMM) and the Renewable Fuels Module (RFM). The EMM represents generation, transmission and pricing of electricity subject to fuel prices, capital costs, and operating parameters like efficiencies. It simulates least cost capacity expansion and also calculates the retail price of electricity at the national and regional levels. The RFM is useful for analysing penetration of renewable energy technologies in NEMS using information regarding cost, performance and daily or seasonal variation of naturally available source of energy [Bernow 1998].

GENIE

GENIE was developed at the Chalmers University of technology,Sweden, as a dynamic non-linear model for Global ENergy system with Internalised Experience curves. It models long term development of the global electricity system, spanning the years 1995-2075 with eight ten-year time-periods. The objective function is to minimise the present value of the total cost of the global electric system. The main utility of GENIE however, is to provide qualitative insights into the dynamics of technological development in the energy system not as a complete tool for general energy policy analysis [Chalmers 2001].

Most of the energy sector models are conceptually similar to the economic equilibrium models discussed in the next few pages. The only difference is that the non-energy markets are not represented here. These models require the energy demand as an exogenous input, which is typically based on other economic and demographic forecasts. The simplification arising from the absence of non-energy markets offers opportunity to have a more disaggregated representation of the energy markets as in GEMINI and FOSSIL2 models. Alternatively it also makes possible to model energy supply sectors in various regions of the world with detailed international trade in fuels.

Economic/Financial Factors Driven Models

Similar to the energy supply/demand driven models, these models are also equilibrium and optimisation based. Aggregate representation of the economy makes it easier to increase the geographic coverage. The model Carbon Emission Trajectory Analysis (CETA) has a single representative global consumer which operates under the labour, capital, electric energy and non-electrical energy markets. Such models have an aggregate macroeconomic growth model coupled with a detailed energy supply model. They have a top-down macroeconomic module linked to a bottom-up energy supply module. ETA-MACRO and MARKAL-MACRO are mainly the models where top-down and bottom-up modules are solved simultaneously. Brief coverage about these models is given below:

MACRO

MACRO model is a two-sector (production and consumption), aggregated view of long-term economic growth. The macroeconomic model MACRO 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. Its strength is that it treats the economy of coherent regions of the world in an integrated fashion and estimates demand of energy. Its weakness is that it has little resolution of technological choices [Grubler 1999]. Due to its versatile nature, the model has been used in conjunction with many other models like MARKAL-MACRO, ETA-MACRO, and MACRO-MESSAGE as described briefly below.

ETA-MACRO:

ETA-MACRO is a general equilibrium model comprising an energy technology evaluation model ETA (Energy Technology Assessment) coupled with a macro economic growth model MACRO. It uses non-linear optimisation. Energy demands and costs take a feedback and get modified on the basis of the information from the economic model. This connection enable the energy model interact with the macro economy of the country/region under consideration.

MARKAL-MACRO:

It is similar to ETA-MACRO model except for the Energy Technology Assessment Model (ETA) being replaced by the much more detailed MARKAL model. In both these models, the macro economy is represented by a single production function with energy, labour and capital as the factor inputs, which does not consider the traditional sector. Over a long planning horizon, the various substitution elasticities are difficult to determine as fixed constants, specially for developing countries. This integration is a good example of combined ‘bottom-up’ & ‘top-down’ modelling techniques for modelling [IRG 1999].

MACRO-MESSAGE:

At International Institute for Applied Systems Analysis (IIASA), Austria, the MACRO model was linked with MESSAGE model to cover the weakness of MACRO and to increase the scope of MESSAGE. In the combined model, MESSAGE computes the minimum system costs to satisfy the projected demand from MACRO. It allows estimation of the economic losses that result, e.g. when carbon constraints are applied to the economy (strength of top-down models) as well as minimum cost suite of technologies needed to meet a given constraint (strength of bottom-up models) [Grubler 1999].

Integrated Models

EFOM and EFOM-ENV

The Energy Flow Optimisation Model (EFOM) is a linear optimisation and simulation energy supply model [RISO 2000]. The model integrates the economic trends driving demand with the technological characteristics of energy systems to estimate the least-cost way of meeting future energy demand. EFOM-ENV (Energy-Flow Optimisation Model/Environment) is a development on the basic EFOM model. A European consortium developed EFOM-ENV used for conducting studies for east European countries. The Asian Institute of Technology modified it further in 1995 to optimise electricity generation and transmission among the seven regions of China. The software uses linear programming to analyse the energy producing and consuming sectors of each region. The EFOM-ENV model is driven by exogenous energy demand assumptions and assumed resource, environmental, and policy constraints. The model contains an energy-environment database describing the energy system being studied. Technologies are explicitly represented by parameters for economic, social, and environmental conditions and linkages among energy systems. Linear programming optimises the energy system according to an objective function defined by model users. The energy database provides the model with quantitative information on energy system structure, technology status, investment and other costs as well as pollutant emissions. With these inputs, the model simulates and optimises primary energy requirements and investments in energy production and energy consumption using various energy conversion processes EFOM-ENV has a flexible model structure and can be adapted to local conditions or changing study requirements. The model structure can be represented in greater or lesser detail. It has been applied to energy and environmental analysis and planning for all European Union member countries and for developing countries including China, Thailand, Indonesia, and the Philippines [Chandler 1998].

PERSEUS

The Program package for Emission Reduction Strategies in Energy Use and Supply (PERSEUS) model for optimising energy and material flow was developed at the University of Karlsruhe, Germany as a tool for strategic planning of energy utilities [Frank 1999]. The model is based on a multi-periodic, mixed integer linear optimisation approach. Existing and future power plant technologies are characterised in great detail by technical, economic and environmental parameters. To account for the growing uncertainty of input data in liberalised markets, stochastic programming techniques have recently been integrated. The evaluation of different GHGs include the Global Warming Potential (GWP) and the radiative forcing which are modelled as time-dependent functions. The model includes reduction measures in all sectors as well as sink options like afforestration and compares all these options simultaneously. The complex network of supply-side options and demand-side options and its interdependencies are represented, and the model minimises 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 minimisation, a profit maximisation approach which better reflects the situation in liberalised markets has been implemented. This approach also allows to consider purchase and sale on spot markets and exchanges for electricity. The model has been successfully used in a number of real-world applications for energy utilities of various sizes. A user-friendly model version has been used by several utilities including the largest supplier of electricity in Germany [Göbelt 2000].

IMAGE 2.0:

IMAGE 2.0 is a multi-disciplinary, integrated model designed to simulate the dynamics of the global society-biosphere-climate system developed in Netherlands [RIVM 2000]. The model consists of three fully linked sub-systems: energy-industry, terrestrial environment, and atmosphere-ocean. The energy-industry model computes the emissions of greenhouse gases in thirteen world regions as a function of energy consumption and industrial production. The terrestrial-environment model simulates the changes in global land cover on a grid scale based on climatic and economic factors. The atmosphere-ocean model computes the build up of greenhouse gases in the atmosphere and the resulting zonal average temperature and precipitation patterns.

GCAM

The Global Change Assessment Model (GCAM) is an integrated set of models, which addresses the global warming issue comprehensively. These models address issues like atmospheric composition, radiative forcing, global mean temperature change and sea level rise based on IPCC (Inter-governmental Panel on Climate Change) scenarios [Edmonds 1993].

AIM

The Asian-Pacific Integrated Model (AIM) is a large-scale model for scenario analyses of greenhouse gas (GHG) emissions and the impacts of global warming in the Asian-Pacific region. This model is developed mainly to examine global warming response measures in the Asian-Pacific region, but it is linked to a world model so that it is possible to make global estimates. The AIM comprises three main models - the GHG emission model (AIM/emission), the global climate change model (AIM/climate) and the climate change impact model (AIM/impact). The bottom-up models are prepared which can reproduce detailed processes of energy consumption, industrial productions, land use changes and waste management as well as technology development and social demand changes. On the other hand, top-down models are prepared for this quantification for estimation of interactions between energy sectors and economic sectors, interactions between land use changes and economic sectors. The original AIM bottom-up components are integrated with two top-down models. through a linkage module. This new structure maximises the ability to simulate a variety of inputs at a variety of levels, and to calculate future Greenhouse Gas (GHG) emissions in a relatively full range analysis [Matsuoka 1994].

2.1.2 Developments in MARKAL Family of Models

Over the years, there have been many developments on the basic MARKAL that was developed as the first version. The MARKAL family of models can now answer a number of different questions related to policy and planning. The MARKAL family of models is benefited from application for variety of strategies and global technical support from international research community. Consequently, various versions can be used to evaluate the following:

- R&D programs
- Energy performance standards
- Business codes
- Demand side management
- Renewable energy programs
- Policies for choice of technologies
- Carbon sequestration projects
- Regional and local energy plans
- Investment management in energy sector
- Clean Development Mechanism (CDM) and Joint Implementation (JI) programs

In addition, many other possibilities are there that can be covered using various members of the MARKAL family. Barring few, most developments as different versions of MARKAL are additive in nature and they can be used in combination with each other as per need. Main versions are described here:

MARKAL

The basic model MARKAL (MARket Allocation) is a bottom-up, dynamic linear programming model of a country'' energy system. Developmental activities related to the model, first developed in the late 1970s for energy planning are now co-ordinated by Energy Technology Systems Analysis Programme (ETSAP), sponsored by the International Energy Agency (IEA). Like most energy system models, MARKAL also interconnects the conversion and consumption of energy. This user-defined network includes all energy carriers involved with primary supplies, conversion, processing, and end-use demand for energy services. The demand for energy end use may be disaggeregated by sector and by end-application within a sector. All these jointly are to be represented in the form of a network referred to a the Reference Energy System (RES).

The optimisation routine used in the model's solution selects from each of the resources, energy carriers, and transformation technologies to produce the least-cost solution subject to a variety of constraints.

Detailed mathematical approach has been described in the chapter-3 of methodology. The user defines technology costs, technical characteristics and demands and as a result of integrated approach, supply side technologies are matched to meet energy demands.

MARKAL-MACRO

MARKAL-MACRO, a result of linking MARKAL (energy sector model) with MACRO (economic model), is a non-linear dynamic optimisation model that links MARKAL, the bottom-up specification of a country's energy system, to a top-down macro-economic growth model. The difference between this and the basic version is determination of levels of demand for energy services. In MARKAL, the user independently determines the energy service demand levels and supplies to the model, however, the effects of energy prices resulting from improvements in energy system or the effects on the economy from the changes in prices are not covered in this approach. In MARKAL_MACRO, once MARKAL finds the least-cost way to meet the demand, energy costs are passed to the MACRO, which related the energy costs to the activity in rest of the economy. Change in costs causes change in consumer utility, and therefore, a modified demand level is returned back to MARKAL, which repeats the cost analysis. The combination MARKAL-MACRO repeats the process until it finds an equilibrium. This work was initially carried out at the Catholic university of Leuven, Belgium and then by GERAD of Canada.

ETL-MARKAL

The pioneering work in the field of Endogenous Learning Technology in MARKAL was done by Chalmers University, Sweden [Mattsson 1997]. Relationships between cumulative world-wide sales and technology investment costs is negative, the curve between the two typically declines with experience due to the process of 'learning by doing'. Work under the project 'Energy Technology Dynamics and Advanced Energy System Modelling (TEEM), involving major modelling centres in Europe, has resulted in the development of an endogenous representation of the learning process in a number of modelling frameworks including MARKAL [Seebregts 1999]. While modelling with ETL-MARKAL for any country, major assumption remains that cost of any technology cannot decrease in a market (country) in response to learning occurring in other market (country). However, such work helps in identifying the 'learning-potentials' of different technologies and segregating them in fast learning, moderate learning and saturated learning categories. This in turn may be helpful in drawing policies for special attention on any technology or cluster of technologies.

Stochastic MARKAL

MARKAL has always been a deterministic model, its deterministic nature restricts the quality of results to depend upon the authenticity and correctness of key input parameters. In a realistic situation, variation in data is almost inevitable that may in turn, affect the results. Therefore, several initiatives at GERAD, COMIN, IIM and ECN have been taken to introduce stochastic nature in MARKAL to cover uncertainties. The key mechanism to include uncertainty in dynamic stochastic programming is by discerning different states of nature that correspond with different values for uncertain parameters and by adding probabilities to these states of nature. In calculating an optimal solution, MARKAL minimises the expected discounted cost of the energy system. In calculating the expected cost for a time-period, MARKAL weights the cost of the energy system in the same way as the deterministic MARKAL model does, up to the moment when uncertainty becomes introduced. After this moment, MARKAL calculates the expected cost by weighting the cost of the energy system for each state of nature with the probability attached to it. The minimum data needed to use the stochastic model is the probability for every state of the defined energy system and the period (year) at which the uncertainty is likely to be resolved. The model creates multiple paths in that year (making a probability tree) and each path is considered as an alternative route for future. The existing model has to be compatible with the Extended MARKAL of Canada [Kanudia 1996], which is the base model used for this development. Some modifications in the OMNI code, with addition of few new tables within MUSS (MARKAL User Support System) are required with inclusion of a scenario index in the name of each variable and constraint for conversion of standard MARKAL into Stochastic-MARKAL.

Multiple Regions MARKAL

This extension of MARKAL can readily combine multiple MARKAL models as a multi-region MARKAL. The user may allow inter-regional exchanges of emission permits (through a joint emission target) and/or of various energy forms. This feature works through input by a FoxPro program to generate the multi-region linear programming. First, a region index is added to the variable and constraint names in each of the Mathematical Programming System (MPS) files. Then each MPS file is distributed in to four files: Rows, Columns, RHS, and Bounds. Individual objective functions are transferred to variables and their sum is used as the new objective function. Variables and constraints are added to replace individual emission constraints with joint ones. All this is controlled by simple parameter declarations [Kanudia 1997]. This version can be useful in analysing policy tools for inter-regional linkage, carbon permit trading and implementation of Clean Development Mechanism (CDM) projects for global carbon mitigation agenda.

MATTER - MARKAL

This enhancement of MARKAL is focused on the GHG gas emission reduction by optimising the flow of materials within the considered system. The MATTER-MARKAL model was developed as a representation of (part of) the Western European economy by the ECN, Netherlands. The economy is modelled as a system, represented by processes and physical and monetary flows between these processes. These processes represent all activities that are necessary to provide products and services. The model contains a database of several hundred processes, covering the whole life cycle for both energy and materials with GHG relevance. Many products and services can be generated through a number of alternative (sets of) processes. The model calculates the least-cost system configuration. This system configuration is characterised by process activities and flows. [Gielen 1998]. Using this variant of MARKAL besides energy and GHG emission related objectives, material substitution, reduction of material consumption through product substitution, waste-recycling strategies can also be analysed. This combination MATTER-MARKAL is especially useful for optimising flow bio-mass feed stocks in the reference energy system.

Limitations of MARKAL

A number of limitations exist for MARKAL. Barring the stochastic version, one major limitation in all other versions is the assumption of ‘perfect information’ and foresight, which precludes incorporation of uncertainty in the analysis. The dynamic nature implies that past decisions and future constraints are included in the decision process. Thus, expected values of parameters like expected emission tax or expected fuel cost bring uncertainties in results. To cover such uncertainties analysis of multiple scenarios is required.

Accuracy of input parameters related to technologies, all the results depend upon the accuracy of demand projections. With time, many factors of the economy change in an unpredictable manner, like coupling of energy demand with GDP growth rate, which cause deviation in actual energy demand from projected demand. Therefore, the accuracy of results cannot be more than accuracy of demand projections.

Renewable energy based technologies, specially wind and photovoltaic systems, observe rapid variation in output due to variation in availability of their sources of energy and an average figure has to be provided. In various studies, it has been found that monthly variation is convenient enough to analyse the performance and it does not include much inaccuracies in results. In MARKAL, the time for averaging performance parameters of renewable energy systems is higher that leads to only very rough assessment of ‘load reduction from conventional plants’ due to availability of renewable energy.

2.1.3 Energy-Environment Planning Studies: World-wide

Energy and environmental planning studies are being conducted world-wide in many countries using various tools and practices. MARKAL alone is being used in more than 40 countries for this purpose. It was not possible to cover all the studies conducted so far, however, a summary of few such studies conducted in some leading countries like US, UK, regions like Europe and studies in countries resembling with India like China, have been mentioned below:

Europe

Europe has been host of many energy and environmental planning studies and related developments. The initial version of MARKAL was developed at KFA, Julich (Germany). Many studies have also been conducted later through STE-Forschung Zentrum, Julich (Germany), ECN-ETSAP, Petten (Netherlands) and other similar nodal agencies to study various energy systems and development of carbon mitigation strategies. MATTER-MARKAL, as explained above, has been developed to analyse the contribution of material system in greenhouse gas emission and potential of mitigation through materials management in Western Europe. Several CDM (Clean Development Mechanism) studies have also been conducted through MARKAL. For Switzerland and Sweden, the cost of reducing carbon emissions by 20% is less if two countries compensate the Netherlands for undertaking greater reductions. Studies have also been conducted for studying penetration of specific technologies. Development of strategies for development of bio-mass energy systems have been evolved through a dynamic analysis conducted by Gielen D. [Gielen 1998a].

United Kingdom

The electricity market in the UK is a liberalised market where cost of electricity from renewable sources is about 20% higher than the standard electricity. Fouquet R. [Fouquet 1998] has analysed how the market for renewable electricity might develop after the liberalisation of the UK market in 1998 and whether it could be significantly used to reduce UK emissions of pollutants and contribute to a more sustainable economy. He has concluded that the renewable energy capacity initially be small and slow to adjust to incentives, initially high demand may drive up prices, discouraging customers from wanting to buy renewable electricity. Low demand, on the other hand, will not provide incentives to invest new capacity. This means that renewable energy cost will not be able to reduce its unit costs of generation, and will not be able to compete in a liberalised market without continued financial support.

United States

Studies have been conducted for reducing the carbon dioxide emissions from the electricity generation in the US. The effects of different policy options were analysed with the model NEMS (National Energy Modelling System) and effects of policies specifically for renewable energy technologies were analysed with model RFM (Renewable Fuels Model). The study revealed that induced diffusion and use of known renewable technologies by supply-side policies can reduce carbon emissions by about 20% by the year 2010. When combined with demand-side policies that accelerate the diffusion of more energy efficient equipment, renewable resources, this overall policy package reduces carbon emissions from the electric power sector by about 25% by 2010 [Bernow 1998].

Canada

Many studies have been conducted in Canada using MARKAL for macro as well as micro level planning. GERAD, a research centre devoted to the theory and applications of operations research and large scale energy and environmental systems has been the hub for activities related to MARKAL in Canada. Carbon mitigation strategies for the province Québec have been evaluated through stochastic programming considering uncertainties involved in stringent measures for carbon mitigation [Kanudia 1996]. In another integrated study for the regions Québec and Ontario, end-use demands have been endogenised and analysed with stochastic programming with multi-region model [Kanudia 1997] for setting local emission targets. The Minimax Regret Criterion also known as Savage Criterion has also been used for selecting decisions under uncertainty, i.e. when the likelihood of the various possible outcomes are not known with sufficient precision to use the classical expected value or expected utility criteria [Loulou 1997].

China

The study conducted jointly by Battele memorial Institute, US, Beijing Energy Efficiency Centre and Energy Research Institute of China [Chandler 1998] was targeted to define least cost electric power and environmental options for China. The study was conducted through assessment of current and future demand of power in China and determination of least cost combination of technologies to meet the demand under different scenarios like controlling sulfur and carbon dioxide emissions and changing fuel prices. Besides suggesting the least cost options, their results have shown that technology alone cannot solve the environmental problem, it has to be linked with legislation, penalties and incentives. They also emphasise need of accelerated R&D on gas, wind turbines, fuel cells, photovoltaics and gasification technologies for promoting sustainable power generation in China. Before this study, a german research group had also conducted a study of the province Guangdong in China using MARKAL.

Indonesia

As a part of scientific co-operation between Indonesia and Germany, MARKAL study was completed in 1993 which dealt with development of economic scenarios, energy demand projections and multi-objective energy supply optimisation. This study was conducted by BPPT (Agency for the Assessment and Application of Technology in Indonesia), Jakarta and KFA (Research Centre, Julich) in Germany. Initially this study did not include environmental aspects but later the scope of study was widened to cover health risks, greenhouse gas emission, and air quality management under different economic scenarios [Kleemann 1994].

Nepal

MARKAL has been used to find directions for the bio-mass energy program for Nepal as it has bio-mass available in abundance unlike many countries in Asia. For this purpose modelling of decentralised rural energy system for three villages of different demographic conditions was conducted [Rizal 1991]. His found that substantial amount of bio-mass needs to be diverted to fodder and fertiliser requirement which will reduce the availability of bio-mass for energy. This study was focussed on the financial and economic aspects of energy planning, however, environmental issues related to energy supply (specially with burning of bio-mass as fuel-wood) have become much important over the years.

2.1.4 Studies Conducted for India and Open Questions

Various energy-environment studies conducted in India for both centralised and decentralised energy planning. A commentary on the work related to energy-environmental planning in India has been given below to present a comprehensive view about the importance of such studies.

- The Tata Energy Research Institute(TERI) had developed model for centralised planning TATA Energy Economy Simulation and Evaluation Model (TEESE) using the approach of the BEEAM model of BNL, US [UNEP 1994]. It optimises the energy flows on an enhanced input-output table based on the developed Reference Energy System (RES). The model has been used to determine costs of CO_2 emission reduction in India and specific studies have been conducted for few selected cities. Later MARKAL was also used to conduct some modelling studies related to the energy demand and environmental assessment in the residential sector of India.

- The Planning Commission Model (a dedicated development) has an inter-fuel substitution module which attempts to integrate 'sectoral optimising supply models' for commercial energy. This model does not include environmental aspects of energy [Sengupta 1993]. The energy policy division of the planning commission of India separately carried out an exercise called 'Sectoral Energy Demand in India' for estimating energy demand using MEDEE-S model (Modele D'evolution de la Demande d' Energie).
- Decentralised models have been applied for micro-level energy planning. A mixed integer linear programming model for technology selection at village level and a linear programming based Goal Programming Model was developed at the Indian Institute of Management, Ahmedabad. Another study conducted at IIM, Ahmedabad, was based on use of MARKAL for different cost and tax scenarios targeted towards penetration of renewable energy technologies in the power generation sector of India [Kanudia 1996a]. Focus of this study has been more towards economic and financial aspects rather than the technology side.
- The Centre De Sciences Humaines, India [Audinet 1998] conducted another major study of Indian power sector. This study also has a tone of economic and financial orientation in which two policy options have been compared. One, the 'business-as-reformed' scenario that includes the then proposed policies by the government such as dismantling of administered prices mechanism (APM) and opening up of power sector for private sector on a large scale. In the second policy option, consequences of the risks involved in the proposed government policy such as lack of co-ordination between public and private sector are analysed. This co-ordination typically, is required as generation is opened for privatisation but transmission and distribution are with public sector requiring co-ordination. They predict that this may result into increased demand-supply gap which will adversely affect the economic growth of the country. For this purpose they have quantified power deficit on terms of loss of GDP which is a major indicator for economic health of any country.
- In India, a World Bank Sector Strategy for greenhouse-gas mitigation is using the EM (Environmental Manual) to identify the scope and costs of strategies to reduce greenhouse-gas emissions [Fritsche 1999].
- The Central Electricity Authority (CEA) has also conducted some studies using EGEAS model for energy planning. As the first stage study titled 'The Fuel Map of India' [CEA 1998] was conducted to forecast the electric energy demand in India and to find the matching power generation capacity requirement considering four technologies. Requirement of fuels was also found for different parts of the country. This study was enhanced by building three scenarios, namely free run-high hydro, free run-feasible hydro and limited coal-feasible hydro case. Fuel requirements for all these cases have been found for the tenth and eleventh five-year plan for the periods 2002-2007 and 2007-2012 respectively.

One peculiar feature of almost all the above studies is that they were either focussed on the energy demand only or too focussed on the economic aspects like GDP growth or on the environmental issues. In most of these studies constraints regarding availability of fuel, restricted growth due to limited infrastructure support have not been given due importance. Further, various technologies have different learning tendencies with respect to investment requirements and performance as well. This means, that the investment requirements are decreasing and new landmarks are being achieved in performance of power plants. Such factors should now be considered in any futuristic study to bring the predictions close to the realities. Efforts are done in this work to cover all such new aspects by making scenarios in this study, hence it will be an almost new approach for analysis of Indian power sector.

2.2 Energy and Environmental Analysis (EEA)

The field of Energy Analysis formally started in 1974 with formulation of guidelines by International Federation of Institutes for Advanced Studies (IFIAS) at Sweden. Later such analysis was extended to cover environmental analysis also with the motive to do the cradle-to-grave analysis of any system or service. Time to time various approaches were developed to accomplish this work. Suitability of any such developed approaches depend upon the characteristics and boundaries of the considered system. An overview of some of these approaches and tools developed world-wide, is given in this section.

2.2.1 Review of Tools and Practices

Prevailing Practices and Guidelines

Process Chain Analysis:

This technique is especially useful for analysis of specific materials and for products that are not made-up from many materials. The method includes backward tracking of all the processes that are involved in producing any material or product or service. Estimation of Cumulative Energy Demand (CED) requires information about the amount and form of energy spent at different stages. All forms of energy are converted into equivalent primary energy before adding up. Detailed explanation of this practice has been given in the methodology chapter. Major limitation of this method is regarding system boundaries as many a times it is not practically feasible to estimate even roughly the amount of energy spent before certain stages. For example production of aluminium requires energy during excavation of ore (Bauxite), transportation of ore, extraction of alumina from ore, purification of aluminium and giving it different shapes according to market requirements like sheets etc.. Even after that transportation of end form, cutting it into proper size or alloying, each stage has some associated energy consumption in one form or other. Exact estimation of energy demand in each of these stages is quite a work which many times is not done though one single study. Separate studies for different stages like for excavation or production of alumina, raw aluminium, aluminium alloy etc are conducted and results of each study are used to supplement studies for further stages for completing the process chain. Between these stages, wherever required, energy demands for additional processes like transportation etc. are also to be incorporated to make the analysis complete. There is a great deal of noise in the results of such studies and the uncertainties associated are also quite unknown [VDI 4600].

Material and Energy Balance

This method is one specific way of conducting simplified process chain analysis. It is useful for analysing any system or assembly that is made of several components and sub-components comprising many materials. Details regarding the use of materials in various components and sub-components are prepared. Using the information about amount of every material used and its corresponding value of energy demand for each unit of material produced total energy demand is estimated. On the basis of information about energy consumption of component manufacturing or assembly processes, or by using pre-determined manufacturing factors (details given in section 3.1.1 later) for various components, energy balances are modified. This exercise requires as a prerequisite, some other analysis (like process chain or input-output analysis) which gives information about specific energy content of any material used in the end product [VDI 4600]. This method can also be extended for conducting environment analysis using specific emission data in place of specific energy content data for energy analysis.

Input-Output Analysis

The methodology allows calculation of total energy demand and total emissions, throughout the economy, due to any economic activity. It deals with an important feature of modern economic activity: inter-industry trading. In input-output analysis we assume that each sector produces a single good, using inputs of other produced goods as well as labour, capital and natural resources. The goods produced (energy in our case) have two possible destinations:

a) they can go to final demand, which includes investment, government purchases and exports.
b) They can go to intermediate demand, and be used as inputs by the manufacturing sectors.

Now, if the final demand for the output from a particular industry increases, there will be need to be a commensurate increase in the inputs to that sector. However, the necessary increase in inputs to that sector must lead to a corresponding increase in outputs from these sectors. These increase in outputs will require the affected sectors to have appropriately increased inputs from these sectors. Clearly, for a reasonable closely interconnected economy, the economy-wide ramifications of altering final demand will form an infinite, though converging, series. To make calculations of the series feasible, we assume that inputs required by any sector are proportional to the output from that sector and there is no substitutability between the inputs. From the input-output table, a matrix of 'technology coefficients' (A) is formed, using the assumed proportionality of inputs and outputs of each sector. We then define the total outputs for the various sectors to constitute a vector 'x' and the final demands of the sector to constitute a vector 'y'. We can then represent the relationship between A, x, and y using the identity matrix 'I', as:

$$(I - A)^{-1} y = x \qquad (2.1)$$

If we know the matrix of technology coefficients and the vector of final demand, then by matrix inversion we can find the vector of corresponding total outputs. The above equation can further be decomposed as:

$$y + [(I - A)^{-1} - I] \cdot y = x \qquad (2.2)$$

The first term indicates the direct effect or final demand and the second term corresponds to the indirect effect i.e. intermediate demand. Using the above explained approach total energy demand and total emissions for any purpose (defined as demand matrix) in any economy can be estimated.

LCA and ISO-14040

LCA is a technique for assessing the environmental aspects and potential impacts associated with a product by compiling an inventory of relevant inputs and outputs of a product system, evaluating the potential environmental impacts associated with those inputs & outputs and interpreting the results of the inventory analysis & impact assessment phases in relation to the objectives of the study. Like process chain analysis and material balance, LCA also needs clear definition of system boundaries and accuracy of results also suffer due to data quality due to data gaps, aggregation, averaging and site specific variations. The international standards organisation provides principles, framework and methodological requirements for conducting LCA studies through ISO 14041, ISO 14042 and ISO 14043 concerning various phases of LCA. ISO 14041 covers goal and scope definition and life cycle inventory analysis, ISO 14042 is concerning life cycle impact assessment and ISO 14043 is pertaining to the life cycle interpretations [ISO 14040].

Eco-Balance

This practice is slightly different from the LCA in the sense that its boundaries do not extend beyond the point where any product is for sale. Therefore, it is not a cradle-to-grave analysis. Results of eco-balance indicate the fuel and energy requirement, raw material consumption, solid waste emissions, air emissions and emissions to water [Bousted I. 1993].

Eco-Indicator

Eco-Indicator is a single value that expresses the total environmental load of a material or process in a single figure unlike LCA results that are slightly difficult to interpret. This serves the purpose of some kind of a yardstick for designers to measure eco-friendliness of any product or process. The LCA method has been expanded to include weighting method for arriving at single value. Data have been collected for most common materials and processes. These materials and processes act as building blocks for finding total value of Eco-Indicator. The higher the indicator, the greater is the environmental impact [PRE 1998].

Exergy Analysis

The term Exergy is also understood as a measure of the 'second law efficiency' in thermodynamics. Normal definition of efficiency (useful output/input) is considered as the first law efficiency that is easy to calculate. Exergy efficiency can be understood as the ratio of minimum theoretical available energy input to the actual energy input. It is considered to be far more informative than the first law efficiency and can be a measure of potential for future improvement. In almost every form of energy, two segments can be made namely useful energy (proportion that can be utilised for work) and non-useful energy. The distribution of useful and non-useful energy depends upon the thermodynamic term 'availability'. Waste heat in any process is escape of some unutilised exergy or waste energy that can derive undesired environmental processes in a non-equilibrium situation. Therefore, experts of exergy advocate for exergy accounting instead of energy accounting as done in much done energy analysis process [Ayres 1998].

Available Tools for Energy-Environment Analysis

Coverage of some of the tools that are used for conducting energy and environmental analysis is given below.

GEMIS/TEMIS

The software named Gesamt Emissions Modell Integrierter Systeme (GEMIS) was developed by the Oeko-Institut, Germany for energy and environmental analysis of systems. It carried database of commonly used materials and processes. The original version is in German but the English version named TEMIS (Total Emission Model for Integrated Systems) was also released later. Using GEMIS/TEMIS life cycle impacts of any energy, transport or material system can be evaluated. The model follows process chain approach uses upstream information about many materials, products and services with respect to many countries in the world. Besides energy and environmental analysis, cost analysis can also be done through this tool in which it works out levelised life cycle cost, investment costs, O&M costs, fuel costs etc. using system and process parameters [GEMIS3.0].

EM (Environmental Manual)

The EM software was prepared as a part of the project 'The Environmental Manual for Power Development' at the Oeko-Institut (Energy Division), Germany. The EM database offers a full set of generic technologies, fuels and fuel-cycles including co-generation, renewable energy systems and energy efficiency appliances. It allows identification of environmental and cost characteristics and comparison of project alternatives for any purpose, usually power generation. It's unique features are inclusion are inclusion of heavy metals and solid wastes among the environmental assessment parameters and ability to analyse levelised life-cycle costs with quantified externalities [EM 1997].

Umberto

Umberto is very useful tool to visualise material and energy flow in any system. Data are taken from external information systems or are newly modelled and calculated by the user. With its comfortable graphic interface, even complex structures can be modelled like the production facilities in a company, process chains, or LCAs. With Umberto, flows and stocks of materials can be evaluated using performance indicators. Scaling per unit of products or per period is possible in the work. In addition, the related environmental costs of the system can also be found and analysed. The software does not only show the relevant flows and environmental effects but also helps to find possibilities for enhancing the system's utility on economic and ecological grounds [Umberto 2000].

Simapro

SimaPro is one of the most widely used Life Cycle Assessment (LCA) software in the world. Introduced in 1990 in response to industry needs, the SimaPro product family facilitates the application of LCA using transparent analysis tools (process trees, graphs and inventory tables). SimaPro allows use of the standard data provided and/or user given data to carry out environmental analysis and pinpoint where the main environmental priority areas are and look for possible improvements [Simapro 1998].

IDEMAT

A computer database developed for designers at the Delft University of Technology, Netherlands. It provides technical information about materials and processes in words, numbers and graphics with special emphasis on environmental information. There are about 365 materials in the database with emphasis on steel and wood. It also indicates the value of the 'eco-indicator' along with other important information for energy and environmental analysis besides general design information like material strength. IDEMAT is a nice integration of an energy-environmental analysis tool in a conventional strength based design tool [IDEMAT].

2.2.2 Some Studies on Energy and Environmental Analyses

Studies in the field of energy analysis started in 1974 after IFIAS defined the methodology and framework related to this field. Numerous studies were conducted from time to time to find the energy input or embedded energy in products and services that later resulted into development of many databases. Power generating systems were also analysed and the relation between energy and output were studied to evaluate the plant utility. Most of the studies conducted in this field are related to photovoltaic systems as the production process is quite energy intensive. Hagedorn [Hagedorn 1989] had analysed the energy input-output details and found the energy payback and yield of PV systems under different conditions of the manufacturing system. Later in addition to the energy analysis, environmental implications were also included in studies conducted for various power generating systems. Schaefer [Schaefer 1992], Kato et.al. [Kato 1997] are some prominent studies covering the lifecycle analysis of PV systems. Besides studying the PV cells modules studies were extended to cover all the peripherals related to PV plants in studies like Kohake D. et. al. [Kohake 1997].

Similar to the analysis of PV systems, solar thermal systems were also analysed by numerous researchers. Mathur and Bansal [Mathur 1998] have done energy analysis of five different types of solar water heating systems in six climatic zones of India. Wagner et. al [Wagner 1995] had done energy and emission balance of solar water heating system in Germany. Wagner and Peuser [Wagner 1997] later have done energy and environmental analysis of different types of solar thermal systems used for different purposes in Germany. Wagner H.J. et. al [Wagner 1999] have also done another study concerning renewable energy systems including wind energy systems in their analysis.

The Danish Wind Turbine Manufacturers Association had the analysis of different wind machines done for them in different operating situations including off-shore installations [Krohn 1997]. Energetics of three types wind energy systems with different hub-heights and demographic conditions were studied by Pick E. [1998]. Similar to the study of environmental analysis of PV systems, energy and environmental analysis (for greenhouse effect) was done by Mathur et. al. [Mathur 1999].

Some conventional power plants were also analysed under the framework of energy analysis. Analysis of a modern coal thermal power plant was done by Heithoff J. et. al [Heithoff 1998] finding the energy requirement at different stages (including plant demolition after useful life), in addition to the operating stage.

Analysis of single type of power plants were extended for replacement of conventional systems by renewable energy systems to assess the relative potential of conservation of primary energy resources. In one such work, Wagner and Bansal [Wagner 1998] and subsequently Guerzenich et. al [Guerzenich 1999] have analysed wind energy, photovoltaic and solar water heating systems for India and Germany. Prakash and Bansal [Prakash 1995] had extended their results of energy analysis of photovoltaic modules to find the effect on overall energy balance of renewable energy promotion program through transient equations. Mathur, Bansal, Wagner [Mathur 2000a] have found a correlation between their results of energy analysis and environmental analysis of few renewable energy systems.

Various studies and data related to different countries and within a country related to different manufacturing conditions shows some macroscopic disagreement in a cursory look. However, such variation is quite expected due to main reasons given here below:

1. Electricity mix in no two countries in the world is absolutely identical. This difference brings in difference in average conversion factor that is used for changing useful energy into equivalent primary energy (explained in detail in methodology chapter). Therefore, even if for two countries, the end use of energy for some purpose is equal and identical in terms of form of energy, while converting them into equivalent primary energy they will yield different values.
2. Even within a country, large variation is possible in energy consumption for the same purpose as it largely depends upon the scale of activity, manufacturing for instance. It is observed that in

production of smaller quantities and in batch production, specific energy consumption and related emissions are higher as compared to large scale production or continuous production system.

3. In two similar plants also, some variation in energy consumption for the same purpose is possible due to difference in process parameters, quality of materials used and also due to difference in dedication towards energy conservation within that system.

However, variation in figures and results of energy analysis studies can be rationalised and suitability of any specific data can be examined and compared with other values. This is possible through the background information often available in relevant literature along with figures and results that explain general characteristics of the system under consideration [Phylipsen 1997].

2.2.3 Selected Methodology for Energy and Environmental Analysis

Out of various practices described in section 2.2.1, choice were restricted to only process chain analysis, energy & material balance and input-output analysis. Scope of other methods like LCA and exergy analysis extends much beyond calculation of Cumulative Energy Demand and Cumulative Greenhouse Gas Emission. Eco-balancing is not a cradle-to-grave analysis and calculation of eco-indicator is almost an extension of LCA converting all effects in terms of just one indicator value. Comparison of the three competing methods for calculation of cumulative energy demand suggests:

- It is not always possible to determine the cumulative energy demand completely and without gaps for all preliminary and parallel stages of the process chain trees in the process chain analysis. The process chains are sometimes very complex and calculation of each part of the chain is not possible.

- The energy input-output analysis usually relies on national data on economic interconnections and energy consumption. Quite often for controlling the size of input-output matrix and sometimes due to difficulty in disaggregation of information, use of aggregated information and reliance on monetary values is almost inevitable. Hence, this method is not directly suitable for finding cumulative energy demand. However, the matrix formation allows representation of almost all stages through their respective coefficients, which is many times not possible in the process chain method.

- The method of balancing of materials and energy in the form of spreadsheets or balance sheets in which use of various materials under major heads representing major components is identified. The energy content of materials used are extrapolated through their quantities used to arrive at the cumulative energy demand of any product. For small systems where the list of materials is not too long, this method is most suitable one. Cases where this list of materials is too long or segregation of quantity of individual material used is not achievable, problem is faced in conducting this analysis. Another problem in this method is definition of system boundaries as use of materials and energy is to be checked within the defined boundaries. Any material if used outside the defined boundary e.g. use of diesel for transportation, does not give its contribution to the results.

Methodology adopted:

Due to merits and demerits of all the three methods discussed above, a combined methodology has been adopted for conducting the energy & environmental analysis. Primarily, the major approach is material and energy balance based and majority of the calculations are done by finding quantity of materials consumed. To cover, energy consumption in various processes like transportation, assembling operations (that are not covered under the scope of material balance) the approach is extended in the form of process chain analysis. Further the energy content of various materials and processes are taken from different databases and literature available. In these databases given information is usually based on either the process-chain-analysis of individual material or drawn from input-output tables of the economy.

2.3 Power Generation in India

Information about various aspects of power generation in India has been collected mainly from three sources:

1) TEDDY 2000: Tata Energy Data Directory Yearbook- 2000. Such data directory is annually published by the Tata Energy Research Institute (TERI), N. Delhi, India [TEDDY 2000].
2) CMIE Report Energy-2000: Report published by the energy division of the Centre for Monitoring Indian Economy, Mumbai, India [CMIE 2000].
3) CEA Reports: Central electricity Authority of India publishes research reports related to power demand projections, supply scenario, development plans, fuel availability and many other aspects of power generation [CEA 1998].

Many other published research works have also been referred besides personal meetings with people related to power plants and governing bodies for data collection. Mention of these has been given in the Chapter-5 itself to facilitate direct referencing of data with its source and with its use in this work.

Chapter-3

ADOPTED METHODOLOGY

3.1 Energy and Environmental Analysis (EEA)

3.1.1 Energy Analysis Methodology

***Energy Analysis**: As per the International Federation of Institutes for Advanced Studies the term energy analysis means 'the determination of the energy sequestered in the process of making a good or service within the framework of an agreed set of conventions or applying the information so obtained' [IFIAS 1974].*

***Cumulative Energy Demand (CED):** The Cumulative energy Demand states the entire energy demand, valued as primary energy, which arises in connection with the production, use and disposal of an economic good(product or service) or which may be attributed respectively to it in a casual relation [VDI 4600].*

Method for Calculating Cumulative Energy Demand (CED)

The method of calculating cumulative energy demand for energy analysis of power generating systems ideally includes the energy demands for each stage usually starting from the extraction of the ore till the demolition of plant at the end of useful life. While doing calculations, it is assumed that the data used for the specific Cumulative Energy Demands (CED) for materials covers all the stages before the material utilisation. Material balances are prepared to find out the total demand of material causing energy demands, indirectly. For preparing the material balances, the whole facility has to be split up into sections, components, sub-component and their respective materials. Using this material balance with specific data for material and energy resources (found by process chain analysis in various studies and databases) it is possible to calculate the Cumulative Energy Demand (CED) for production (CED_P) of any system.

The total CED_P of a plant has been found through:

$$CED_{P,total} = \sum_{Components} CED_{P,Components} \quad (3.1)$$

with

$$CED_{P,Component} = \sum_{Material} \left[ced_{material} \cdot m_{material} \right] \cdot F_P \quad (3.2)$$

where: CED_P = *cumulative energy demand for making the plant*

$ced_{material}$ = *specific cumulative energy demand of each material*

$m_{material}$ = *weight of each material*

F_P = *manufacturing factor of the component*

The energy demand of production processes (e.g. forming, cutting, assembling operations) is taken into account by multiplication of the material-based energy demand with the manufacturing-factor F_P. Such factors have directly been assigned to the materials based on the understanding of the manufacturing processes but few of them have also been experimentally found as there is still a shortage of information about its value for many processes. However, value of the manufacturing factor depends upon the nature and extent of additional work required for using the material in certain plant. It is quite possible to find two different factors assigned to the same material in different components. This is due to the reason that the amount and nature of processing differs from case to case hence, requiring a different factors to incorporate the energy demands of their respective manufacturing processes.

Transportation of the equipment and machinery consume considerable amount of energy hence it has also been taken into account. Generic data for various modes of transportation has been used [GEMIS3.0]. Calculations have been carried out taking average values of distances for transportation. A sensitivity analysis has also been done to find the possible variation in CED due to change in mode of transportation and distance. The following formula has been used for finding the energy demand for transportation:

$$CED_{Transport} = ced_{Transport} \cdot d \cdot m \qquad (3.3)$$

where: *d = distance for transportation*

m= weight for transportation

ced $_{Transport}$ *= specific energy demand for transportation (in MJ/T/km)*

The energy demand for utilisation of system (power generating system) includes the energy consumption for running or utilising the plant. This demand includes fuel requirement and power requirement for running control devices and other supporting activities. In case of renewable energy technologies, this demand is very less as compared to non-renewable technologies. The energy content of renewable sources like energy of solar radiation, wind energy are not included in $CED_{Utlisation}$ as the very purpose of energy analysis is to find load on natural resources or more commonly known as fuel reserves. In contrast to renewable energy systems, in conventional systems, contribution of this part in total CED becomes most important as the primary energy consumption through fuel consumption comes out to be much more than any other cause for primary energy demand.

The energy demand for the disposal and recycling of the material used in the plant after the end of plant life has also been included where available. This value may be negative in some cases if some energy is saved due to recycling of materials. However, it is usually positive, as the gain in recycling is less than the energy demand for dismantling or disposal of facility.

The following formula has been used for finding the total energy demand for a plant over lifetime:

$$CED_{Total} = CED_{Production} + CED_{Utilisation} + CED_{Disposal} + CED_{Others} \quad (3.4)$$

Use of CED in Energy Analysis

Energy Pay Back: *This term indicates in how many years any system will be able to repay the amount of energy invested for setting up and making it functional over the lifetime. With the assumption that the energy output of the system doesn't vary with the ageing of plant, it is defined as the ratio of the total or cumulated energy demand of a system to the energy delivered or conserved in one year. The terms are expressed as equivalent primary energy, unless specified.*

Energy Yield Ratio: *This term is defined as the ratio of the total energy output over entire lifetime to the total energy input as CED. Both the input and output energy are expressed in terms of equivalent primary energy, unless specified. This term indicates how many times of the energy investment is returned or repaid by the system. For a sustainable system, this ratio should be equal to or more than unity.*

The energy payback and energy yield ratio have been found using the following formula:

$$EYR_{net,primary} = \frac{W_{net,primary}}{CED_{total}} \quad (3.5)$$

$$Payback = \frac{CED_{total}}{AnnualW_{net,primary}} \quad (3.6)$$

where

$$W_{net,primary} = \frac{W_{net,physical}}{PE} \quad (3.7)$$

here: $W_{net,\ physical}$ *= Total energy output over lifetime (in useful form)*

$W_{net,\ primary}$ *= Primary energy equivalent of* $W_{net,\ physical}$

PE = Potential efficiency of energy conversion

The two terms EYR and payback have been expressed in the diagram given below as figure 3.1:

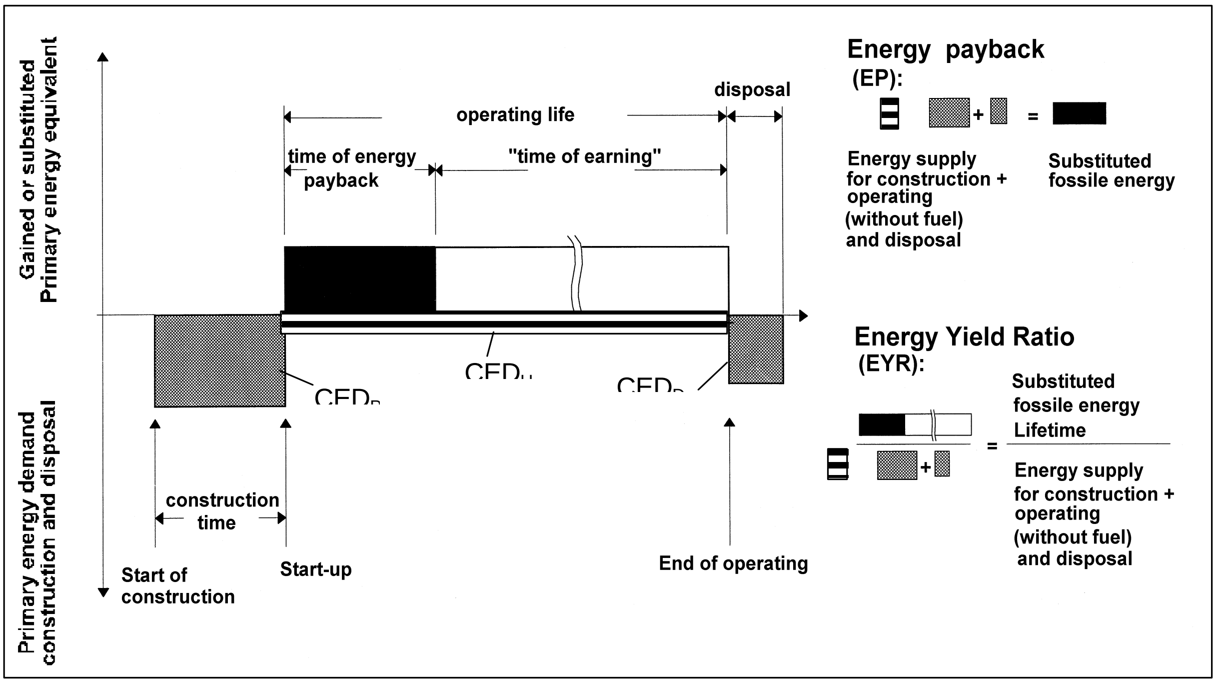


Figure 3.1: Energy Payback and Energy Yield Ratio

The method used to calculate the equivalent primary energy output from the physical energy output is by dividing the net energy output for example a coal power plant by the average potential efficiency of coal steam-electric stations. The average potential efficiency (PE) is the reciprocal of the factor for supply of grid electricity and is equal to the average efficiency. For India the factor has been found to be 3.03 and the potential efficiency 0.33, using the following formula:

$$F_{supply,electricity} = \frac{\sum_{fuel} input_{fuel} \cdot F_{supply,fuel} \cdot F_{supply,powerplant}}{output_{electricity}} \qquad (3.8)$$

where: $F_{supply,\ electricity}$ = *Factor for supply of electricity*
$input_{fuel}$ = *Primary energy input as fuel*
$F_{supply,\ fuel}$ = *Factor for supply of fuel*
$F_{supply,\ powerplant}$ = *Factor for supply of energy by power plant*

3.1.2 Environmental Analysis Methodology

For environmental analysis the preliminary work is similar to that of the energy analysis. The method of calculating cumulative emissions of power generating systems ideally includes the emissions at each stage starting from the extraction of the ore till the demolition of plant at the end of useful life. Material balances prepared for carrying out energy analysis can also be used for this analysis. The basic difference being that in this case instead of energy demand, emissions are to be considered for all the materials and processes involved. One major difference of this analysis with the energy analysis is that there are several emissions associated with different materials and processes. Each emission has its own importance with respect to the effect it causes, e.g. greenhouse effect, acidification, nitrification. As the scope of this study is confined to the greenhouse effect only, emissions having a non-zero global warming potential are considered in this study. They have been converted into equivalent CO_2 using their respective of Global Warming Potentials in the formula given below for calculating the Cumulative Greenhouse Effect (CGHE) for each material:

$$CGHE = \sum_{Emissions} \left[m_{emission} \cdot GWP_{emission} \right] \qquad (3.9)$$

where: CGHE = Cumulated green house effect for any system

$m_{emission}$ =Weight of emission released

$GWP_{emission}$ = global warming potential factor for emission

Global Warming Potential: *It is the ratio of greenhouse effect caused by unit mass of any gas to the greenhouse effect caused by the same mass of carbon dioxide gas. It is expressed with reference to defined time horizons.*

Values of the global warming potential for the emissions considered are as given in the table 3.1 given below. Suffixes used with the GWP in the three columns indicate considered lifetime of emissions.

Table 3.1: Global Warming Potentials of major emissions

Emission	GWP_{20}	GWP_{100}	GWP_{200}
Carbon dioxide	1	1	1
Methane	35	11	4
Dinitrogen oxide	260	270	170
Dichorodifluoromethane	7100	7100	4100

Source: [Heijungs R. 1992]

Similar to the studies conducted by IPCC, FCCC and many other studies, in this study also GWP_{100} (for 100 year time) of various emissions have been considered for estimating the global warming.

Using the material balance with specific data cumulative greenhouse effect for different materials, the Cumulative Greenhouse Effect (CGHE) for production ($CGHE_P$) of any system can be calculated through the following formulae:

$$CGHE_{P,total} = \sum_{Components} CGHE_{P,Components} \tag{3.10}$$

with

$$CGHE_{P,Component} = \sum_{Material} \left[cghe_{material} \cdot m_{material} \right] \cdot F_P \tag{3.11}$$

where: $CGHE_P$ = *cumulative greenhouse effect for the plant*

$cghe_{material}$ = *specific cumulative greenhouse effect of material(kg* CO_2 */kg material)*

$m_{material}$ = *weight of material*

F_P = *manufacturing factor*

Similar to the energy analysis, the following formula has been used for finding the total cumulative greenhouse effect for a plant over lifetime:

$$CGHE_{Total} = CGHE_{Production} + CGHE_{Utilisation} + CGHE_{Disposal} + CGHE_{Others} \tag{3.12}$$

Use of CGHE in Environmental Analysis

Emission Coefficient*: This term is defined as the ratio of the total cumulative greenhouse effect (CGHE) to the total physical energy output (energy in usable form, usually electricity) over entire life of the system. CGHE is expressed in terms of weight of equivalent carbon dioxide emission. Physical energy output for example is expressed as heat output in case of solar water heating system and as electricity in case of PV or wind energy system.*

The value of emission coefficients for different systems have been found using the following formula:

$$EC = \frac{CGHE_{Total}}{W_{net,physical}} \tag{3.13}$$

where: *EC = Emission coefficient (usually in kg* CO_2 *equivalent per kWh of physical energy)*

$W_{net,\ physical}$ *= Energy output over lifetime in kWh*

Value of emission coefficient, however, can also expressed in terms of equivalent primary energy output using the potential efficiency of energy conversion as explained in the section 3.1.1.

The quality of data available for emissions is not very accurate due to the complexities associated with process chain analysis. Some values had to be calculated and extrapolated for few materials based on other related information like energy demand and values available for other materials. Major emissions considered in this study are carbon dioxide, oxides of sulphur, dinitrogen oxide, oxides of nitrogen (other than dinitrogen), methane, non-methane volatile organic carbon (NMVOC), and particulate matter.

3.2 Energy Planning with MARKAL

3.2.1 Salient features of MARKAL

General Characteristics

As mentioned in the introductory note about MARKAL in section 2.1.2, it is a large scale model intended for long term analysis of energy systems at the level of a province, state, country or region. It was first developed in the early 1980's by a consortium of members of International energy Agency (IEA) working within the Energy Technology Systems Analysis Programme (ETSAP). Two institutions, Brookhaven National Laboratories (BNL), USA and Kern Forschungs Anlage (KFA) renamed to be Froschung Zentrum (FZ), Julich, Germany, served as hosts for the above project. Many modifications were later were made in MARKAL to make it more versatile and capable in the forms of different versions like MARKAL-ED, MARKAL-MACRO, MARKAL-MATTER. The model's acronym stands for MARket ALlocation, revealing the intention of its developers to make a tool that analyses market potentials of energy technologies and energy carriers.

MARKAL is a multi-period-long-term model of the integrated energy system of a geographic or political entity, which encompasses the procurement as well as the transformation and the end use of as complete a mix of energy forms as is desired. A MARKAL model consists of mainly the description of a large set of energy technologies, linked together by energy and/or material flows, jointly forming what is called a Reference Energy System (RES). RES is the structural backbone of MARKAL model for any particular energy system, and has the great advantage of giving 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 or useful energy demand. Feasible solutions are obtained only if all specified end use demands for energy for all the time periods are satisfied. The user exogenously supplies these demands in the model. Once the Reference Energy System has been specified, MARKAL generates a set of equations that hold the system together. In addition, MARKAL possesses a clearly defined objective, which is usually chosen to be the long term discounted cost of the energy system. The objective is optimised by running the model, which means that configuration of the RES is dynamically adjusted by the model in such a way that all model equations are satisfied and the long term discounted system cost is minimised. In this process MARKAL computes a partial equilibrium of the energy system at each period, i.e. a set of quantities and prices of all energy forms and materials, such that supply equals demand at each time period. A variety of real life restrictions and constraints can also be supplied to MARKAL for making the solution more realistic.

The energy system as visualised by MARKAL is as shown in figure 3.2.

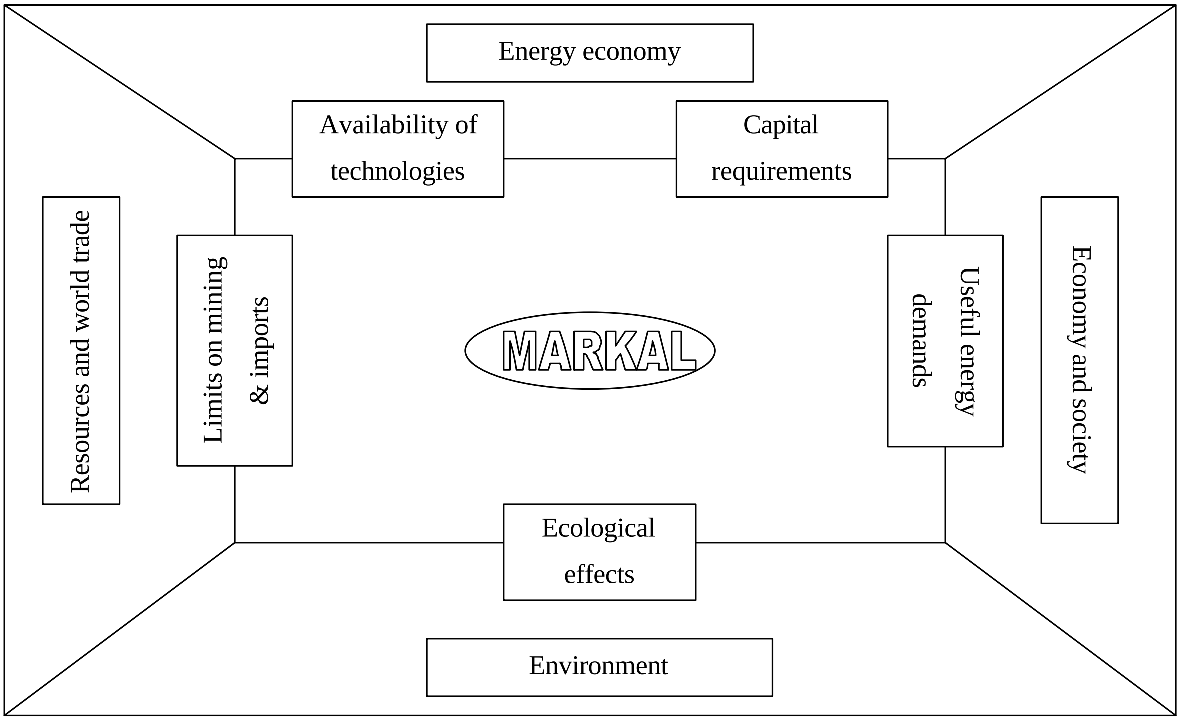


Figure 3.2: Interfaces of the model in MARKAL

The Mathematical Structure of MARKAL

MARKAL consists of a set of equations and inequalities, collectively referred to act as constraints, and one objective function which is typically taken as total discounted cost of the energy system. Mathematical expressions for constraints and objective function are written in terms of two types of quantities namely, the decision variables and the parameters. The decision variables are unknown quantities which the model is meant to determine, whereas, the parameters are known quantities, specified by the user. The variables and parameters are selected so as to enable the model to state precisely all important constraints of the system. In MARKAL there are five sets of variables as given below:

INV (k, t): the investment in technology k, at period t;
CAP (k, t): the capacity of technology k, at period t;
ACT (k, t): the activity of technology k, at time period t;
IMP (i, t): the amount of energy import, of form i, at period t;
EXP (i, t): the amount of energy export, of form i, at period t.

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

a) Flow conservation

For the flow of each form of energy, the consumption must not exceed the availability through the inequality;

$$\sum_k out_{k,f}.ACT(k,t) + \sum_s IMP(f,t) - \sum_k inp_{k,f}.ACT(k,t) - \sum_d EXP(f,t) \geq 0 \qquad (3.14)$$

where:

k = any technology in the model

f = any form of energy

$out_{k,f}$ = amounts of energy form f produced by one unit of activity in technology k

$inp_{k,f}$ =amounts of energy form f consumed by one unit of activity of technology k.

b) Demand satisfaction

Demand dem_d for each type of end use of electricity, is satisfied at each period through the condition:

$$\sum_k CAP(k,t) \geq dem_{d,t} \qquad (3.15)$$

where,

$dem_{d,t}$ is the demand for end use of energy(electricity) at period t, and the summation is done over all the technologies k, which produce energy for demand d. Demand in the above expression is the gross demand that includes losses in the transmission, distribution & utilisation, incorporated through different parameters in the model.

c) Capacity transfer

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

$$CAP(k,t) - \sum_p INV(k,p) \leq resid_{k,t} \qquad (3.16)$$

where,

$resid_{k,t}$ is the 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 of technology k.

d) Capacity utilisation

In each technology, k's activity must not exceed its installed capacity at any time period t.

$$ACT(k,t) - util_k.CAP(k,t) \leq 0$$

(3.17)

where,

$util_{k,t}$ is the annual utilisation factor of technology k. The electricity generation technologies may have single annual utilisation factor or seasonal utiisation factors the sum of which should be less than unity.

e) Source capacity

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

$$\sum_k inp_{k,f}.ACT(k,t) \leq \sum_i srcap_{f,t,i}$$

(3.18)

where,

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

f) Growth constraint

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

$$CAP(k,t+1) - (1+growth_k).CAP(k,t) \leq 0$$

(3.19)

where,

$growth_k$ is the maximum allowable growth factor for each technology at time period t.

g) Emission constraints

These constraints specify the upper limit on emissions of certain pollutants by the system as a whole. These limits can be imposed in two ways, separately for each time period or cumulatively over the whole time horizon. For these constraints to be active within the model, emission coefficients must have been defined for all polluting technologies.

h) Objective function

It is the main expression, which is optimised by the model. Usually it is the total discounted system cost (TDSC) which is the combination of five types of costs;

TDSC = Technology Cost + Import Cost – Export Revenue – Salvage Value + Emission Fees

(3.20)

where,

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

Imports cost: is the discounted cost of imports of energy. It involves the IMP variables.

Exports revenue: is the discounted sum of exports revenue earned from export of energy outside the reference energy system. It involves the EXP variables.

Salvage value: is a term which accounts for 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 decisions towards the end of the horizon. Without this corrective term, the model would tend to avoid new investments toward the later periods, since such investments would be productive over a short duration only.

Emission fees: is paid if the model user specifies a cost per ton of pollutants, within the ENV table of parameters. It 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 is an alternative to using emission constraints. Another name of given to this fee is pollutant tax.
The set of variables and constraints constituting the model of the energy system is defined in the form of a coefficient matrix as shown in the figure 3.3.

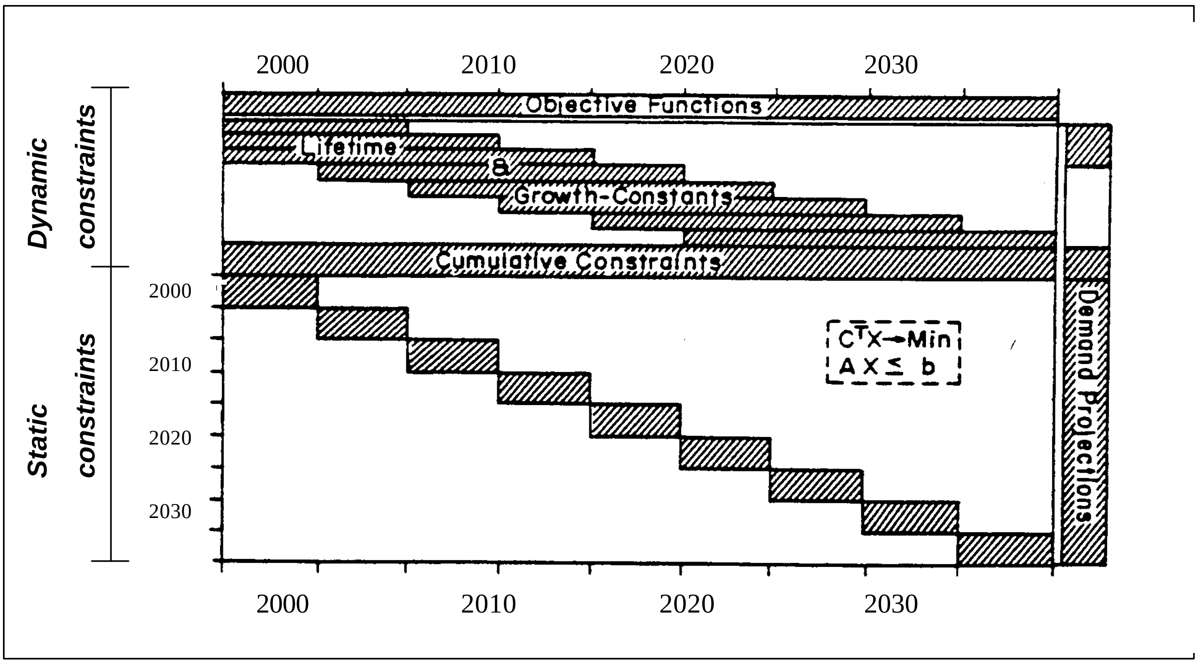


Figure 3.3: Matrix formation in MARKAL

On the X-axis of the figure 3.3 is the time horizon of study with segments representing length of each time period of the study. Y-axis, has been divided onto two sections, lower section representing static or 'time independent' constraints. The portion of dynamic constraints covers 'time dependent' constraints. Bars travelling horizontally in the portion of dynamic constraints represent dynamic constraint relevant in different time duration. They may cross boundaries of single time periods, start from any point of time and end at any time within the time span of study. The lowermost bar in the dynamic growth section represents cumulative constraints such as upper limit on cumulative consumption of coal, is relevant over entire period of study and is to be satisfied in each time period. Small boxes in the lower part of the figure represent static constraints that are confined to certain time period of the study only such as bound on capacity in certain time period, which may have different value for each time period and each value is relevant for its time period only. Therefore, in contrast to the length of boxes in the upper part, lengths of boxes in this part do not exceed length of single time period. The entire figure represents the main matrix and each box individually represent a sub-matrix with non-zero coefficients. Complexity of matrix depends upon types of energy carriers, conversion technologies, emissions and their linkages in the reference energy system.

The method of arriving are optimal solution with MARKAL is linear programming based as almost all the decision variables can be rational numbers. Had it been the case of integer constraints and decision variables, integer programming method would have been more suitable where at every stage variables have to take integer values only. In situations where only some variables have the limitation of being integers, mixed integer programming method is most suitable. In these cases, values obtained are to be converted into integer values first for proceeding towards next step or iteration for which the Branch & Bound method is most commonly adopted technique. In this technique, for example if 3.45 is the value of any variable, this value can be taken as either 3 or 4. Therefore, one sub-program will take the value 3 and other sub-program proceeds with value 4 making two branches of he solution. The advantage of doing this is that the solution obtained is more accurate but the number of sub-programs grows exponentially with every step, making the computing time far more than the linear programming approach where the value is rounded-off to the closest integer. Cases in which, many integer variables exist, mixed integer programming is better as rounding-off at many places sometimes magnifies the inaccuracy. In our case, few variables like installed power generation capacity are normally integers only but the 'order-of-magnitude analysis' suggests that variation due to conversion from rational to integer does not have significant effect on the results. Hence, linear programming method as adopted by MARKAL has been found to be the most suitable method for this study.

3.2.2 Modelling through MARKAL

Inputs and outputs in MARKAL

a) MARKAL inputs

The expressions for constraints and objective function mentioned in section 3.2.1 suggest that MARKAL requires extensive data to operate. Most of the data requirement is concerning individual technologies whereas others concern energy forms, carriers and demands. The database is logically organised into classes and tables. Each class contains a list of elements. These are classes of technologies of energy sources, demands carriers etc. each class is used by some MARKAL constraints in order to limit the range of application of summation indices. Figure 3.4 and 3.5 show organisation of the main MARKAL elements into classes and subclasses.

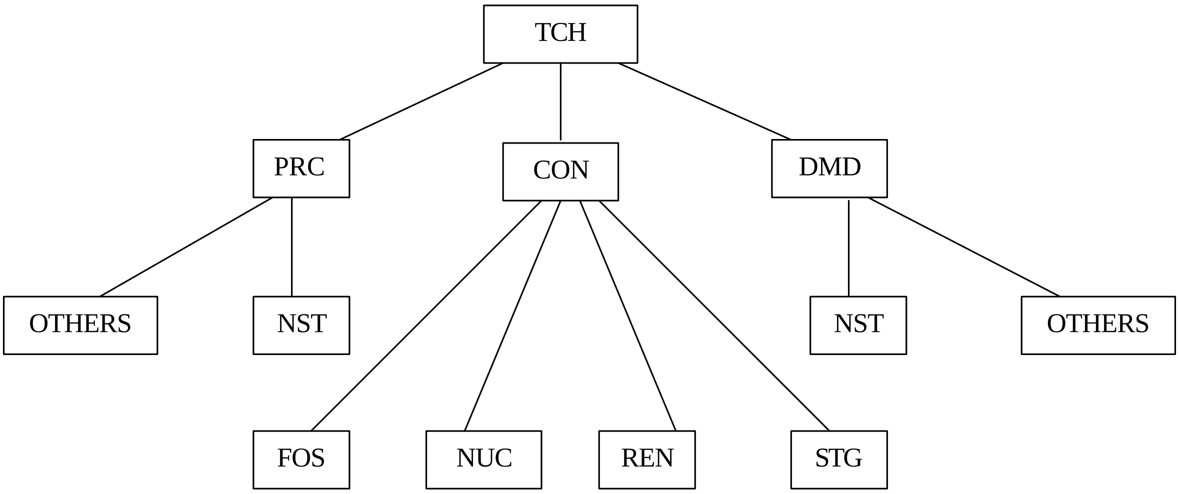


Figure 3.4: Classes of technologies in MARKAL
(explanations of short terms used have been given in text)

The main class named TCH as shown in the above figure contains all technologies involved in the Reference Energy System. Its subclasses are CON (conversion technologies commonly known as electricity producing technologies), PRC (other energy producing and transformation technologies e.g. coal extraction), and DMD (end use technologies). Each of these classes in turn may have subclasses for example CON class consists of base and non-base power plants covered under FOS (Fossil fuel Based Technologies), NUC (Nuclear Power Technology), REN (Renewable Energy Based Technology) and STG (Energy Storage Technology).

Class PRC contains technologies for obtaining all energy sources such as coal extraction. Its sub-classes are based upon the method of utilisation of facility such as NST (Night Storage System), OTHERS sub-class shown in figure include categories like Fix Capacity Utilisation, and Dummy

Technology. Similarly the class DMD has sub-classes indicating additional characterisation of technology into NST (Night Storage System), and OTHERS (covering all other types).

Similar to the main class TCH, another main class is ENT that contains all energy carriers covered in the Reference Energy System. It is subdivided into various classes like ENC, ELC and LTH. Class ENC covers standard energy carriers, represented by sub classes EFS(Fossil Fuels), ESY(Synthetic fuels), ENU(Nuclear fuels), ERN(Renewable energy carriers) and EHC(High temperature heat or cooling). The sub-class EFS is further divided into three more classes describing physical state of fossil fuels in solid, liquid or gaseous state by classes SLD, LIQ and GAZ respectively.

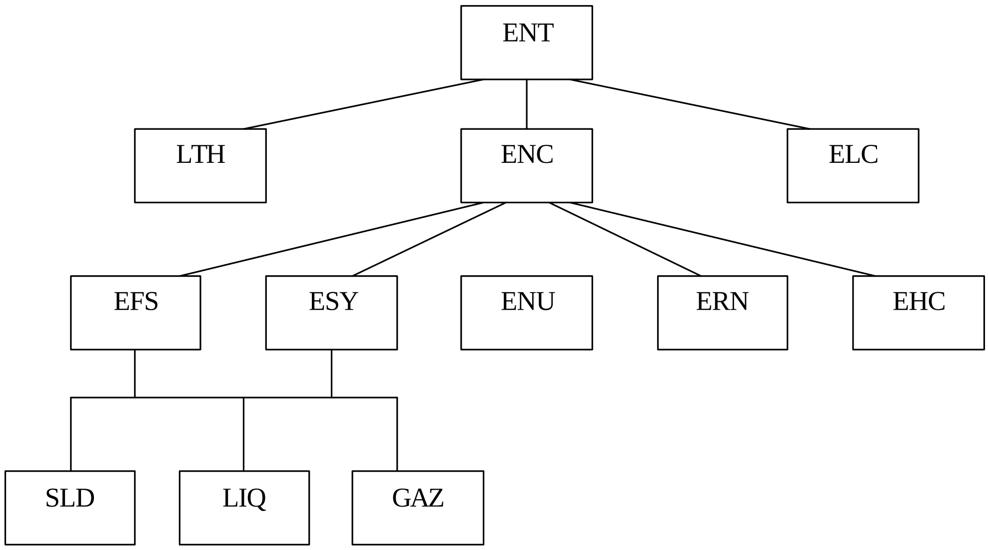


Figure 3.5: Classes of energy carriers in MARKAL
(explanations of short terms used have been given in text)

Quantitative information about the elements of the above mentioned classes is stored in the form of 'MARKAL tables'. They are used as parameters in the constraints and objective function of the model. Organisation of tables is as explained below:

Table DM(DM) contains the exogenous demands for all energy services at all periods. This set of data constitutes the demand scenario.

Table DMD(DMD), PRC(PRC), and CON(CON), one for each technology, contain the amounts of inputs and outputs per unit of activity of the technology, as well as the efficiency of the technology.

Table TCH(TCH), one for each technology, contains the other techno-economic information of each technology, such as, residual capacity at each time period, date of first availability, life duration, growth factor, and the four types of costs except emission costs.

Table ENV, one for each pollutant in the model, contains emission coefficients of all technologies.

Table SRC(ENC), one for each imported, exported, or locally extracted form of energy; contains the acquisition cost of energy form at source, as well as the amounts of each energy form available.

Table CONSTANT and UNITS contain the general parameters of the model, such as discount factor, number of years per time period, starting year and various units.

b) MARKAL outputs

A typical MARKAL solution consists of the following:

a) A set of investments in all technologies selected by the model at each time period. This set indicates the level of new investment in terms of plant capacity in each period for each technology.

b) A set of operating levels of all technologies. MARKAL suggests optimum utilisation level of each technology in each period. This is expressed in terms of percentage utilisation of installed power generation capacity. MARKAL results may even suggest partial utilisation levels for any technology in any period.

c) The quantities of each fuel produced, imported, and/or exported at each period. Based on the information about plant capacity and plant utilisation, MARKAL also gives the total quantity of each energy carrier/fuel required or consumed in the energy system in each period. It also gives information about the quantity of energy carrier/fuel consumed by each technology in each period.

d) The emission of pollutants at each period. In the input parameters, if sufficient information about different emissions is provided in terms of emission coefficients for each technology, this result set provides values of total emissions due to utilisation of different technologies.

e) The overall system's discounted total cost. It is the minimum value of operation of the reference energy system under the defined energy demand levels for each period of study. It is the value of the objective function of the model.

Due to the multi-period nature of model, some results of one period become inputs for next period over the entire time span of the study. Values in relevant tables get modified endogenously for calculations of the next step. For example, existing capacity in the first period gets appended by the decision of capacity expansion for this period. Hence, for the second period, value of the existing capacity is internally modified by adding the amount of capacity expansion recommended for the first period.

3.3 Linking Energy and Environmental Analysis with MARKAL

3.3.1 Concept of Dynamic Analysis

Usual practice of carrying out energy analysis and utilisation of its results has been explained in section 3.1. In normal practice, results related to CED and EYR are analysed without considering the time frame into account as equations for such analysis are not having any transient term. The new approach presented in this section enhances the widely accepted 'static' energy analysis to 'dynamic' energy analysis along with utilisation of results of static and dynamic analysis into macro level planning process. One such approach is developed through the planning tool MARKAL in the manner explained in the following sections.

The term Cumulative Energy Demand for certain power plant indicates load on primary energy resources through consumption of different forms of physical energy like electricity, fossil fuel etc. The physical energy required to build any power plant obviously comes out of the pool of gross physical energy available for total consumption within the country/region/province under consideration. Thus, the gross demand can be split into two segments. One, energy demand as CED of different power plants and second one being the remaining demand for all other sectors of economy. The total requirement of energy (EDM) for capacity expansion at any point of time 't' depends upon the number and nature of plants being built up, which can be found using the following formula:

$$EDM\,(CONST)_{k,t} = n_{k,t}.CED_k \tag{3.21}$$

where,

$EDM(CONST)_k$ = physical energy required for construction of n plants of technology k.

CED_k = cumulative energy demand of each plant of technology k.

The total energy demand for construction of different types of plants using different technologies can then be found through:

$$EDM\,(CONST)_t = \sum_k EDM\,(CONST)_{k,t} = \sum_k n_{k,t}.CED_k \tag{3.22}$$

This extra demand of energy for building new power generation capacity affects the national energy balance in the way expressed below:

Demand at any point of time 't' is a sum of active energy demand (demand other than CED as explained above) and the energy demanded for construction of power plants.

$$EDM(TOTAL)_t = EDM_t + EDM(CONST)_t \tag{3.23}$$

Due to the gestation/construction period or time required for construction of power plants, the construction activity has to be started ahead of the time in which it is required for utilisation. For an exponential growth pattern, the number of plants of certain technology k, at any point of time t, can be found from:

$$n_f(t) = n_0 e^{a(t-t_c)} \tag{3.24}$$

where,

$n_f(t)$ = number of functional/operating plants at point of time t

n_0 = number of functional/operating plants at time t=0

t_c = construction time for each plant

a = factor for growth rate

The number of plants under construction at time t, can thus be found through:

$$n_c(t) = n_0 e^{at}(1 - e^{-at_c}) \tag{3.25}$$

Total energy required for construction of plants of technology k, at point of time t is found using:

$$EDM(CONST)_{k,t} = CED_k . n_0 e^{at}(1 - e^{-at_c}) \tag{3.26}$$

Total energy output from all operational plants of technology k can be found from:

$$EN_{k,t} = (en_k). n_0 e^{a(t-t_c)} \tag{3.27}$$

where,

$EN_{k,t}$ = total annual energy output from technology k at time t.

en_k = annual energy output from one plant of technology k.

Therefore, availability of energy for satisfying active demand (demand other than CED), can be written as:

$$EN(ACTIV)_t = \sum_k EN_{k,t} - \sum_k EDM(CONST)_{k,t}$$

(3.28)

where,

EN(ACTIV)$_t$ = active demand of energy (demand other than CED) at point of time t,

Requirement of this active demand of energy should be satisfied by the combination of all technologies for a self-sustainable growth of power generation capacity. As is clear from equations of dynamic analysis, value of maximum growth rate for any technology depends upon the Cumulative Energy Demand and the annual energy output.

Feasible solutions of equations 3.28 through equations 3.26 and 3.27 are bounded by the upper limit of growth factor 'a'. This means that there is finite maximum value of growth factor 'a' for the equation of balance between demand and supply. It is because a growth rate higher than the maximum value suggested by the balance equation would result into disturbance of the dynamic balance between energy demand and supply causing creation of an energy sink instead of an energy pool.

3.3.2 Method of Linking Energy and Environmental Analysis with MARKAL

As explained in section 3.2.1, MARKAL takes maximum growth rate as a user defined optional constraint in the model. This constraint is usually a time series parameter, value of that may be different for each period of study in case of each technology. It can be expressed in terms of units of plant capacity (GW in this case) or in terms of maximum allowed investment expressed in monitory terms or even in terms of percentage of capacity in use at any period.

The value of a maximum self sustaining growth rate obtained by the approach discussed in the previous section can thus be used in MARKAL as a constraint. This upper bound on growth is to be adhered even if the affordable growth rate based on other constraints like infrastructure support, fuel availability etc. is higher than the former growth rate suggested by EEA.

Use of maximum growth rate individually for different technologies obtained from the dynamic analysis in MARKAL would thus integrate the two different analysis. The benefit of linking or integrating both analyses is that instead of relatively less mathematical and less scientifically supported value of growth constraint, we have a more logical and scientifically obtained value of constraint. The former may be based upon non-tangible factors and may involve high and unknown degree of uncertainty, however, in the new approach, parameters are tangible and uncertainties can also be estimated to a large extent.

Following this new approach, we incorporate the results of energy analysis as additional new parameters in the MARKAL model. Though, a better approach, instead of calculating the bound on growth rate externally in a separate analysis and then supplying it for MARKAL analysis would have been calculating it within the MARKAL analysis itself. Since it would have necessitated modification of optimisation equations through modifications in the GAMS code (language on which the mathematical part of MARKAL works), which is out of the scope of this work, this external linking approach has been developed.

In the process of linking of output of energy analysis with MARKAL, two different scenarios have been made to have a feel of possible variation in the final results. These scenarios have been explained as case 1 and case 2.

Case 1

In this case maximum growth rate is found corresponding to a situation where energy demanded for building new capacity of certain technology is equal to the energy supplied by the operational plants of the same technology. The hypothesis behind this condition is that expansion of capacity of each technology is a separate sub-program of the main capacity expansion program as they are individually governed by different bodies. Hence, each sub-program should be self-sustainable in itself without causing any extra burden on the other sub-programs of capacity expansion for other technologies. It is also assumed initially that in the final solution all the technologies are not observing their maximum growth levels. It is quite obvious that less preferred technologies would be allocated a lesser growth rate in the solution, keeping the margin for supply of energy for the active demand. Assuming the condition when all the technologies are having maximum self sustaining growth rate, in that situation despite having generation of considerable amount of energy, no energy would be available for consumption as active demand. Such a situation is unlikely to arise, as aggregate effect of different growth rates of different technologies is much higher than the aggregate growth of energy demand.

Therefore, for the case of a self-sustaining capacity expansion program, expressions on the right hand side of equations 3.26 and 3.27 must balance. If the energy demand for construction (equation 3.26) is more than the energy output (from equation 3.27), the program of capacity expansion becomes a net energy sink rather than serving the purpose of source of energy for other activities. The limiting condition for each technology k, can be expressed as:

$$(en_k).n_0 e^{a(t-t_c)} \geq CED_k.n_0 e^{at}(1-e^{-at_c}) \tag{3.29}$$

For the above equation, maximum value of growth factor ‘a’, can thus be obtained by rewriting the above inequality for limiting condition in the following form and solving it for maximum value of ‘a’:

$$\frac{en_k}{CED_k} = \left[e^{a.t_c} - 1\right] \tag{3.30}$$

Case 2

Instead of making all the sub-programs for all the technologies self-sustainable individually; another approach for planning may be by making compulsory for each sub-program to contribute towards the national energy demand besides taking care of its own expansion. Meaning, self-sustaining is not the sufficient condition for each sub-program but it has to contribute towards the remaining part of the national demand also. This approach is in contrast to the previous case, where there may not be any net contribution from a fast growing technology. Due to the very nature of MARKAL, the cheapest technology (having least discounted total cost) is likely to get more growth as compared to the costlier ones. Consequently as per case-1 the limiting condition would arise for cheaper technologies but not for the costlier ones and utilisation of cheaper technologies will be more than the case-2. Hence, the overall system cost in case-2 would be higher than the first case. In this case, only one part of the gross annual energy output from each technology is considered for reinvestment for construction of new plants for capacity expansion. This factor of permissible reinvestment can be same for all technologies or different for each technology, depending upon the promotional priorities. In this study, a common factor for all the technologies has been considered for this purpose. A typical common factor can be found from the share of total CED in the gross energy demand in the base year. An underlying assumption while using this factor is that the same proportion of energy can be spared from the energy pool, for capacity expansion in all the periods. The balance of energy input and output can then expressed as:

$$\left[(en_k).n_0 e^{a(t-t_c)}\right]x \geq CED_k.n_0 e^{at}(1-e^{-at_c}) \tag{3.31}$$

where, x is the factor representing percentage of energy output from that can be used endogenously for capacity expansion instead reinvesting the entire output for the purpose.

This approach will definitely yield a lower value of maximum growth rate for capacity expansion for each technology that can be obtained by rewriting the above equation in the following form and solving it for maximum value of growth factor ‘a’:

$$\frac{x.en_k}{CED_k} = \left[e^{a.t_c} - 1\right] \tag{3.32}$$

The energy re-investment factor ‘x’ has a potential of affecting the growth factor ‘a’ by a large extent. Therefore, a judicious decision about ‘x’ is necessary for making results of the analysis more feasible and useful. This factor has been estimated by two methods. One method has been through an analogy between financial and energy sectors. The factor representing percentage of national budget allocation for power generation capacity expansion has been used to represent the amount of energy re-investment from the total energy pool. Another approach for finding the factor ‘x’, is through the CED_P values for different power plants using the following formula:

$$x = \frac{\sum_k SPCED_k . CAP_{k,t}}{\sum_k output_k} \tag{3.33}$$

where,

$SPCED_k$ = CED for unit capacity of technology k

CAP_k = new installed capacity of technology k

$Output_k$ = Total power output from technology k

This approach finds the percentage of energy re-investment in the base year thus de-coupling energy demand for new plants from active demand of energy i.e. national energy demand excluding demand as CED for different plants.

Solving equation 3.30 for maximum value growth rate a_{max}, we get the following expression for each technology k, in case 1:

$$a_{\max,k} = \frac{\ln(\frac{en_k}{CED_k} + 1)}{t_{c,k}} \tag{3.34}$$

and similarly, using equation 3.31, maximum growth rate for each technology k, in case 2 can be calculated by:

$$a_{\max,k} = \frac{\ln(\frac{x.en_k}{CED_k} + 1)}{t_{c,k}} \tag{3.35}$$

Reduction in maximum growth rate of each technology is clearly visible due to an additional term ‘x’ appearing in the logarithmic expression value of which is always less then one. The possibility of variation in the factor ‘x’ has been covered under the sensitivity analysis in chapter 8.

3.4 Other Aspects of Methodology

The methodological aspects related to the modelling of power generation sector have been explained in the chapter 5 along with description of the Reference Energy System and method of analysis of the power sector through making different scenarios have been explained in chapter 6. This has been done to facilitate linking of the method used with the data that has been used to represent the considered energy system.

To explore the possible variation in results due to variation in various key parameters, sensitivity analysis has also been carried out by for possible variation in important parameters. Such investigation has been done individually for each of such parameters as well as for different combinations of parameters to cover possibility of variation in one parameter with respect to the other. For example there may be some variation in investment requirement for coal power plant with or without any link with variation in fuel price. Such an approach has enabled the author to comment about the robustness of the model and results.

Chapter-4

ENERGY AND ENVIRONMENTAL ANALYSIS OF SELECTED POWER GENERATION SYSTEMS

The Energy and Environmental Analysis of power plants, as explained in section 3.1 gives information about resulting depletion of primary energy resources due to their making, utilizing and even demolition at end of life and provides indicators for assessing their usefulness. Energy Yield Ratio, Energy Payback Period and Emission Coefficients are such major indicators. The process of conducting this analysis requires collection and synthesis of information even up to micro levels that becomes quite complex as the number of parts and their sub-components increase.

4.1 Selection of Technologies

Due to the reason mentioned above, Energy and Environmental Analysis of all the technologies considered was falling much beyond the limitations and scope of this study. Separate detailed studies have been conducted from time-to-time for each type of power plants [Schaeffer 1992], [IEA 2000],. As there may be variation in results of such studies depending upon country-to-country, analysis of few technologies has been done to check the validity of results in Indian context for use in this work. This validation was necessary specially for the two types of renewable energy systems considered in the MARKAL analysis, namely, wind energy systems and photovoltaic systems, as the annual output largely depends upon local climatic conditions unlike other systems. Moreover, EEA of one of conventional power generation plant has also been done to find correctness of results mentioned in other studies in Indian context. Initial part of this chapter covers above three cases of Energy and Environmental Analysis.

For remaining technologies, results of two prominent studies [Schaeffer 1992], [IEA 2000] have been directly used for calculations in dynamic EEA section of this chapter for linking with MARKAL analysis as described in section 3.3.2.

4.2 Energy and Environmental Analysis

4.2.1 Wind Energy System

Wind Energy Converters transform the kinetic energy of wind to electricity at a site having a minimum wind velocity value of which varies from machine to machine. For a good site moderate wind-velocity with a smooth velocity profile is always desired. A site having very strong wind with rapid fluctuations may not give as much output as a site having relatively slower but steady wind profile throughout the year. Output of the wind energy converter depends on the third power of the wind velocity, hence it is very much sensitive to the wind speed. Other factors that affect the output are air density and area swept by rotor. Energy in wind is given by the following formula:

$$P = (1/2).r.A.v^{3} \quad (4.1)$$

where: P: Power in wind (kW)

r: Density of air (kg/m^3)

A: Rotor area (m^2) normal to direction of wind

v: Wind speed (m/s)

In India, there are more than 50 wind monitoring stations where the direction and velocity of wind are continuously measured [Mani 1993]. On the basis of the measured data Weibull's size and shape factors are determined that take into consideration the possible variation of wind velocity within the considered unit of time (normally one hour, one day or one month). Measurements at heights 10 meters and 20 meters above the ground level are used for finding the Hellmann's coefficient that correlates variation of wind speed with change in altitude. Using this coefficient, wind velocity at any height can be found using Hellmann's formula given below:

$$V_h = V_{10}\,(Z/10)^{a} \quad (4.2)$$

where: V_h: air velocity at height h

V_{10}: air velocity at 10 meter height

Z: height h

a:: Hellmann coefficient

The Hellmann's coefficient (∝) is a characteristic feature of each location and it's value primarily depends upon the geographical details of the site. It's value is lower above sea or in areas close to sea as there is not much variation of wind velocity with height as compared to other sites. In areas having rough topography on the surface this coefficient has a higher value indicating a rapid increase in wind velocity with height. Such an increase occurs due to the reason that the rough surfaces have a slowing effect on the layers of air close to surface due to friction and obstacles due to buildings, mountains , trees etc.. For calculating air velocity at the hub-height, the Hellmann's coefficient plays an important role. Therefore, one representative location for each of the three categories based upon the Hellman's coefficient or alternatively known as roughing factor has been chosen for this analysis. These categories are coastal, near coastal, and inland sites. In India, places Rameshwaram, Bamanbore and Sultanpet are considered in this study for representing coastal, near coastal and inland sites respectively.

The yearly velocity profiles of these stations are shown in figure 4.1.

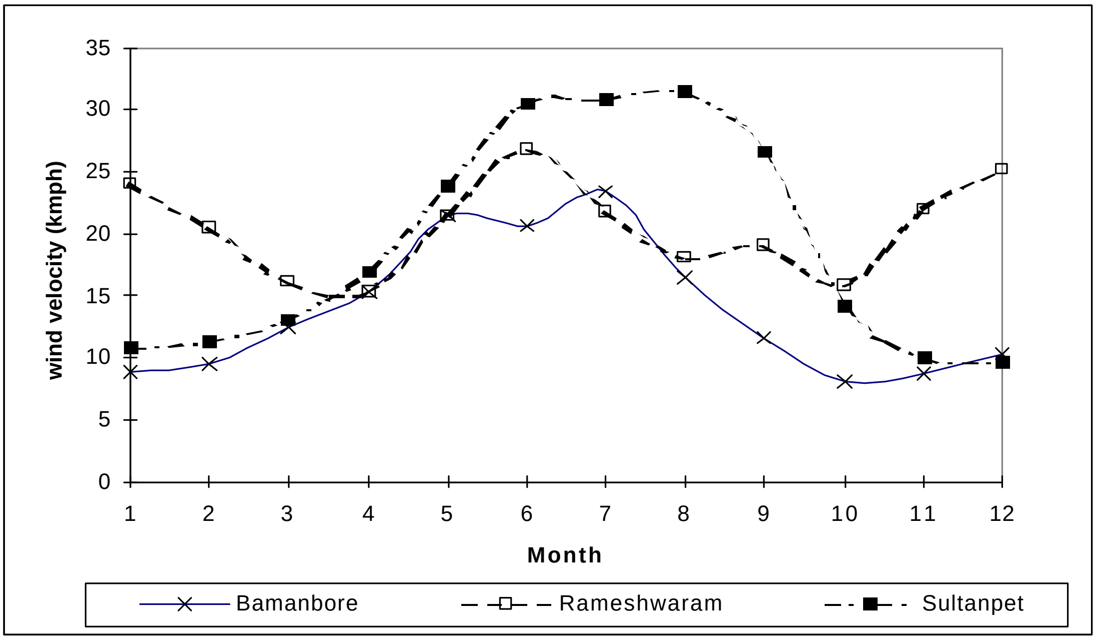


Figure 4.1: Yearly Wind Velocity Profiles at Selected Sites in India (at 10 meter height)

Wind energy converters are specified by the capacity of maximum power generation. Out of the wide range of wind energy converters 1.5 MW converters have been chosen for this analysis as these are the one of the largest capacity wind machines and represent the state of art in this field. Following are the main features of this machine:

- Peak Output: 1.5 MW (at 12.5 m/s and above)
- Hub height: 67 meter, Rotor blade diameter: 66 meter
- Cut-in speed: 2.5 m/s, Cut-out speed: 25 m/s

Due to the inertia of components there is a minimum wind speed required to produce any output, this minimum wind speed is called cut-in speed. Cut-out speed is that wind speed at which the power generation is automatically switched off to protect the machine from damages.
General assumptions used in this analysis are [Pick 1998]:

- Wind velocity distribution within a year and within a month follows Weibull´s distribution.
- Lifetime of plant is 20 years.
- Coating on rotor blades is required as maintenance after 10 years of life.

Energy Analysis of Wind Energy System

The entire wind energy converter has been divided into six functional parts for carrying out material and energy balance. Following are those main parts:

- Rotor blades
- Generator
- Rest of housing
- Tower
- Grid connection
- Foundation

Separate material and energy balances for each of the above six parts have been prepared and given in appendix-2. The approach discussed in chapter 3 has been followed. Table 4.1 gives contribution of major components in the total CED of the considered Wind Energy Converter (WEC) including the energy demands due to transportation and maintenance.

Table 4.1: Break-up of Cumulative Energy Demand of 1.5 MW wind energy converter

	Rameshwaram (Coastal)		Bamanbore (Near Coastal)		Sultanpet (Inland)	
Component group	Energy content (GJ)	%	Energy content (GJ)	%	Energy content (GJ)	%
Rotor blades	1147	8.2	1147	8.3	1147	8.3
Generator	2877	20.6	2877	20.9	2877	20.8
Rest of machinery	1814	13.0	1814	13.2	1814	13.1
Tower	3774	27.0	3774	27.5	3774	27.2
Grid connection	1512	10.8	1512	11.0	1512	10.9
Foundation	1493	10.7	1350	9.8	1350	9.7
Assembly	402	2.9	402	2.9	402	2.9
Transportation	743	5.3	657	4.8	746	5.4
Maintenance	23	0.2	33	0.2	55	0.4
CED	13960	100	13742	100	13852	100

The CEDs for the three selected sites are different for the following reasons:

- The type of foundation depends upon the nature of soil at the site. Normally, at coastal sites a deep foundations are required that have a higher CED. Appendix-2 also shows calculation of CED for both types of foundations.
- Distance for transportation of machinery and equipment is different.

The sensitivity analysis for finding change in CED due to change in type of foundation and distance for transportation shows that variation in the values of CED is within 2% of the value for the coastal site and henceforth, unless specified, for all calculations value of CED 13960 GJ has been used.

Figure 4.2 shows the contribution of various components in the total CED of the WEC considered. It clearly indicates that the largest energy demand arises from the tower followed by the generator as the second largest energy demanding component.

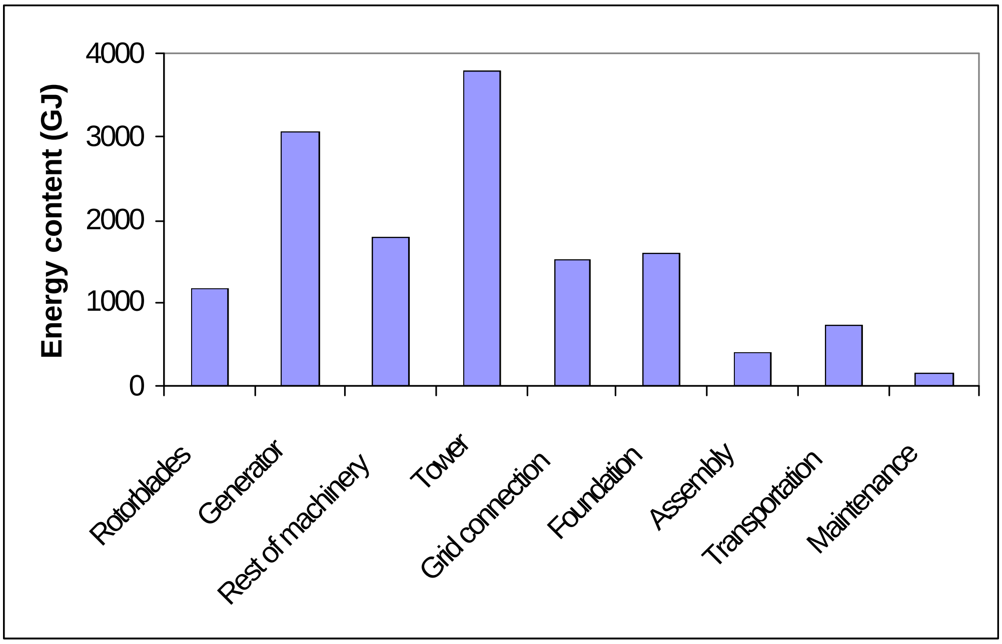


Figure 4.2:Contribution of various components in total CED of 1.5MW WEC

Energy Harvest (Output)

For calculating the energy output or energy harvest the wind energy data for the three sites of India have been taken as shown in figure 4.1 [Mani93]. For all the three sites, wind velocity data of past three years average have been considered. Power curve that is a plot of power output in kW v/s wind velocity in m/s, has been used to find the energy harvest. The power curve is a characteristic of each type of wind mill. Figure 4.3 shows the power curve of the considered 1.5 MW machine.

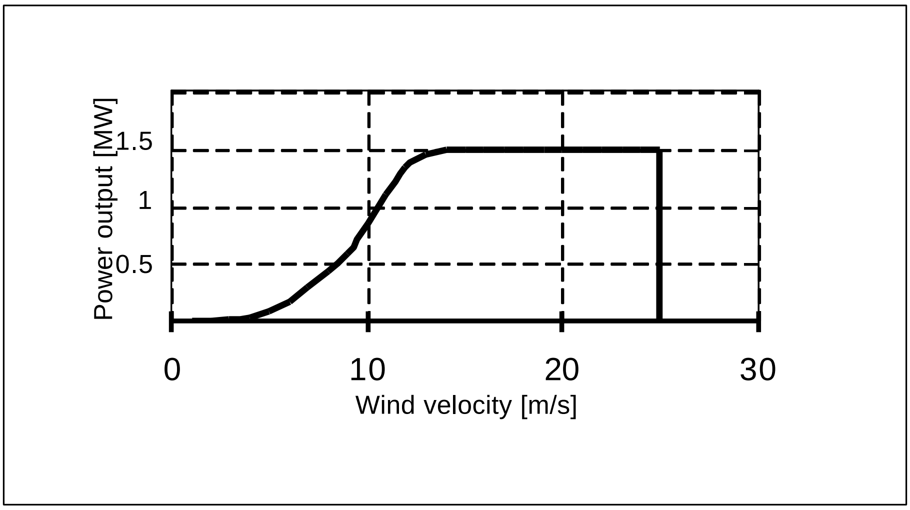


Figure 4.3: Power Curve for 1.5 MW Wind Energy Converter

About 0.35% of the energy harvest is used by the system itself as prescribed by the manufacturer for running different devices and controls [Pick 1998]. Therefore the net harvest is 99.65% of the total harvest. Annual electricity output or energy harvest for Rameswaram has been found to be 6033 MWh, highest among the three considered stations For Bamanbore 2121.5 MWh and for Sultanpet 1846 MWh output have been arrived at using the power curve.

Energy Payback and Energy Yield Ratio

For calculation of the energy payback, first of all, the net harvest has been converted to equivalent primary energy dividing it by the potential efficiency of energy conversion of the national electricity mix (33%) using equation 3.7. Table 4.2 shows total and net harvest as well as the energy payback for the selected sites. In addition, the primary Energy Yield Ratios have also been found using equations 3.5 dividing the lifetime energy output by the total CED of the system. The physical energy Yield Ratios have been found by substituting the physical (electrical) energy output in place of primary energy output in equation 3.5.

Table 4.2: Yearly Energy Harvest, Payback and EYR of WEC in India

	Coastal (Rameshwaram)	Near coast (Bamanbore)	Inland (Sultanpet)
Energy harvest (MWh/a)	6054.5	2129	1852.8
Energy $harvest_{net}$ (MWh/a)	6033	2121.5	1846
$W_{prim, net}$ (GJ/a)	65814.54	23143.63	20138.18
CED (GJ)	13960	13742	13852
Payback (yrs.)	0.21	0.59	0.69
$EYR_{net, physical}$	31.11	11.11	9.59
$EYR_{net, primary}$	94.29	33.68	29.07

As can be seen in table 4.2, the EYR of 1.5 MW WEC varies over a wide range as the energy harvest at the three sites are widely different. Though an $EYR_{primary}$ of 29.07 in case of inland site is low as compared to the value 94.29 of the coastal site, but it is sufficiently attractive in itself, to establish the utility of WECs at such sites even.

Environmental Analysis of Wind Energy System

Using the same material balances prepared for finding the CED and the values of specific emissions associated with the materials, total emissions associated with WEC is found. Table 4.3 shows the emissions associated with major parts of the wind energy converter. Detailed emission balances are shown in appendix-3. The cumulated green house effect(CGHE) is calculated in terms of equivalent CO_2 using the global warming potentials for a lifetime of 100 years as mentioned with table 3.1 in chapter 3.

Table 4.3: Break-up of CGHE of 1.5 MW wind energy converter

Component	CO_2 (kg)	CO (kg)	SO_2 (kg)	NOx (kg)	CH_4 (kg)	Particulate (kg)	CGHE (kg CO_2)
Rotorblades	15364.5	9.3	9.8	21.4	35.6	1.4	22176.1
Generator	205752.5	2072.8	317.2	422.9	64.8	2112.4	317995.5
Rest of machinery	110102.5	1323.3	152.5	116.5	30.0	97.9	141451.1
Tower	255206.3	3236.3	361.9	254.0	53.1	74.4	323108.5
Grid connection	99639.3	311.9	162.8	225.4	49.5	1429.8	159977.8
Foundation	61528.9	859.9	178.5	74.5	3.4	40.9	81022.7
Total	747593.9	7813.6	1182.8	1114.9	236.3	3756.9	1045731.5

Values in last column and row differ from actual total due to rounding off

The above table clearly indicates that the largest two contributors for the cumulated greenhouse effect are the generator and the tower. The chart shown below as figure 4.4 indicates the percentage share of each component in the total of individual emissions and also in overall greenhouse effect.

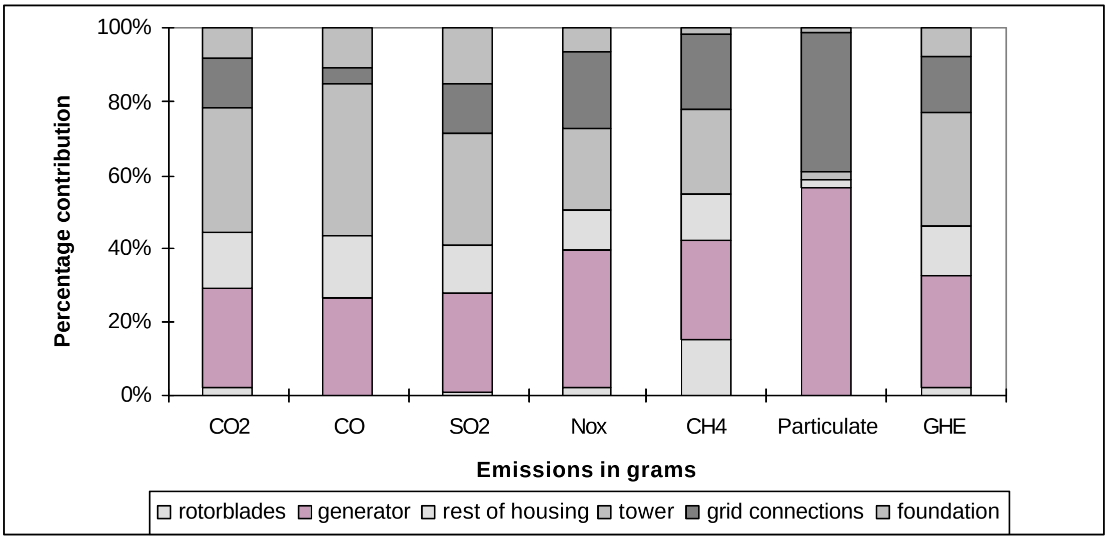


Figure 4.4: Contribution of various components of 1.5MW WEC in total emissions

Using the value of CGHE as shown in the last column of table 4.3 and the energy harvest over the lifetime of 20 years (found in energy analysis part), values of CGHE per unit energy delivered have been obtained. Table 4.4 shows the results of the above mentioned computation. Due to more energy harvest, the green house effect per unit energy is lowest at Rameswaram (coastal) and highest for Sultanpet (inland) due to least harvest..

Table 4.4: Emissions per unit energy delivered by Wind Energy Converter

City	Rameswaram (coastal)	Bamanbore (near coastal)	Sultanpet (inland)
Output(lifetime) GJ_{el}	434394	152747	132934
CGHE (kg. CO_2 equivalent)	1045731	1045731	1045731
Emission coefficient (kg CO_2/ GJ_{el})	2.41	6.84	7.86

4.2.2 Solar Photovoltaic System

Mono crystalline photovoltaic modules are manufactured in India by private and semi-government producers. The Central Electronics Limited (CEL), Sahibabad is a leading semi-government organisation where silicon wafers are purchased and processed to make solar cells and photovoltaic modules subsequently. The wafers are indigenously manufactured at other plants and are also imported from foreign countries to meet the manufacturing demand. Following are the specifications of a module produced by CEL:

- Type: Single crystalline
- Output: 35W_{peak}
- Module dimensions: 1006 X 398 mm.
- Module life: 20 years
- Cell efficiency: 13% at standard test conditions (1000W radiation, 25°C temperature)

Energy Analysis

For finding the CED of photovoltaic power plants, first energy analysis of PV modules was conducted. As the plant does not manufactures silicon wafers for itself, the energy content of silicon wafers has been taken from studies related to sources from where wafers are imported [Kato 1997], [Völlmecke 2000], [Guerzenich 2001]. The energy consumed for the processing of wafers into modules has been taken based on the information provided by the sources at the plant of CEL for the year 1997 [CEL 1999]. Due to propriety restrictions put by CEL, more details cannot be given hence, a single final figure of energy consumption has been used. For the maintenance of the PV system, replacement of glass after every seven years has been taken into account. Table 4.5 shows the break up of material and energy demand for a 35 W_P PV module indicating the dominating share of mono crystalline silicon wafers.

To estimate the effect of transportation of modules on the CED due to large distances in India, a sensitivity analysis has been carried. Since the specific energy demands of various modes of transportation e.g. railways, road, are different separate analysis has been done for two prominent modes in India. It shows a possible variation of less than 1% in the total CED for transportation as the weight of modules is very less in comparison with the embedded energy.

Table 4.5: Energy Balance of 35W_P PV Modules Produced in India

Component	Sub component	Specific CED (MJ/unit)	Quantity	Unit	Manu. Factor.	CED MJ/module	% of plant
PV module	Wafer	42	35	watt peak	0	1470	61.6%
	Aluminium frame	225.3	0.96	Kg	0.1	237.92	10%
	Glass cover	15	3.24	Kg	0	48.6	2%
	Electricals	100	1	Kg	0.16	116	4.9%
	Processing	9.03	35	watt peak	0	316.05	13.2%
Support (steel)		18.36	4.76	Kg	0.15	100.50	4.2%
Maintenance	Glass cover	15	6.48	Kg	0	97.2	4%
Sum						2386.27	100%

For extending the energy analysis of PV module to analysis of PV power plant, again other studies have been referred as in India, no PV power plant has been built at full commercial level, though there are few very small plants working as pilot projects. It has been found from those studies that about 15-25% increase in CED/W_P takes place for this extrapolation [Kato et. al. 97]. Taking the most commonly found value of 20%, extrapolation has been done to obtain the CED for the photovoltaic power plant, CED/W_p as obtained from table 4.5 have been modified to yield a value of 81.81 GJ/kW_P of the plant.

Energy Yield Ratio and Energy payback

Due to widely varying climatic conditions and therefore varying values of irradiation and ambient temperatures in different parts of the country, one representative city of each climatic zone has been chosen for analysis of energy payback period and energy yield ratio. Table 4.6 gives the annual energy output in the representative city of each climatic zone and payback period and EYR at these places. As can be seen the $EYR_{primary}$ for various locations lie between 4 to 5 and the energy pay back period between 5 to 6 years. The competitive figures for wind energy plants are much better even for the inland site.

Environmental Analysis

The environmental analysis of PV modules produced in India was also carried out using the details of the module produced by Central Electronics Limited, Sahibabad. Approach was similar tothe approach used for carrying out energy analysis. The wafer manufacturing process being the single largest contributor, dominates among all the materials and processes. Share of various components of a module is shown in table 4.6.

Table 4.6: Contribution of components in CGHE of 35 W_P PV module

Component	Sub component	Material	Quantity	Unit	CGHE (kg CO_2)
PV module	wafer	mono crcystalline Si	35	Watt peak	156.16
	frame	aluminium	0.96	kg	6.26
	cover	glass	3.24	kg	6.01
	electricals		1	kg	9.45
	processing		110.63	MJ(el)	30.06
Support		steel	4.76	kg	1.29
Maintenance	cover	glass	6.48	kg	12.03
Sum					**221.31**

The CGHE value for the 35 W_P module can also be expressed as 6.32 kg CO_2/W_P capacity. In some other studies, this value has been found to vary from 3.0 kg CO_2/W_P to 7 kg CO_2/W_P for mono-crystalline PV systems [Kato 1997], [Schaefer 1992] ,[Guerzenich 2001].

Table 4.7: Energy Payback, Energy Yield Ratio and Emission Coefficients of PV plants in Indian climatic zones

Climatic zone	Hot & dry	Moderate	Composite	Cold & sunny	Warm & humid	Cool & cloudy
Rep. City	Ahmedabad	Bangalore	Delhi	Leh	Madras	Srinagar
Annual Output/W_P (kWh_{el}/W_P)	1.44	1.31	1.32	1.29	1.33	1.33
Primary energy equivalent of annual output (MJ)	15.71	14.29	14.40	14.07	14.51	14.51
CED/W_P (MJ)	81.81	81.81	81.81	81.81	81.81	81.81
Energy Pay Back Period (years)	5.21	5.72	5.68	5.81	5.64	5.64
$EYR_{Physical}$	1.58	1.44	1.45	1.42	1.46	1.46
$EYR_{Primary}$	4.80	4.37	4.40	4.29	4.43	4.43
Emission Coefficient (kg CO_2/kWh_{el})	0.18	0.19	0.19	0.2	0.19	0.19

4.2.3 Coal Power Plant

Coal power has about 75% share in the total installed capacity of power generation in India. Most of the plants are using coal that is having calorific value around 17500 kJ/kg. In this study this type of coal is referred as hard coal which though is not a common term in India but is widely used in Germany and other European countries.

Energy Analysis of Indian Coal Power plant

One 4X210 MW coal power plant has been analyzed to find the agreement of results with other energy analysis studies carried in different parts of the world. The entire plant was sub-divided into several major sections for convenience in identifying each equipment/component and its role in the power plant. This in turn has helped in finding the amount of materials used through each equipment/component for preparation of the material balance for energy analysis. Summary of the analysis has been presented in table 4.8 below and component-wise details have been presented as appendix-4:

Table 4.8: Cumulative Energy Demand of 4X210 MW Coal Power Plant in India

Description of Part / Component Group	Weight of material (kg)	CED (TJ)	Percentage of total CED
Mechanical equipment (boiler, turbine, lube oil facilities etc.)	47096380	1978.1	71.5%
Hydro-technical equipment (cold water, ash handling, fly ash, bottom as systems etc.))	3495154	146.8	5.3%
Electrical equipment (generators, transformers, switch gears, electrolizers etc.)	2930020	29.3	10.6%
Control and instrumentation equipment (instruments for process control in various parts)	502700	118.1	4.3%
Civil / Structural works (Framework, platforms, tanks, ducts etc.)	21514300	322.7	11.7%
Civil work (for hydro-technical equipment)	344440	23.1	0.8%
Ash disposal system	128900	53.9	2.0%
Total (material)	**76011894**	**2935.7**	**100%**
Transportation and installation	--	587.1	(20% of $CED_{material}$)*
Grand total	**--**	**3522.9**	**--**

** taken on the basis of [Heithoff 1998]*

It was not possible to find break-up of materials used beyond certain stage for many components like control panels etc. Energy balance has been carried out on the basis of the material having the largest share in its weight and generic data available through other similar studies and databases [GEMIS3.0], [IDEMAT], [Emil]. Results have been found to be in agreement with other such studies, discussed later in this section.

Energy Yield Ratio

For calculation of energy yield ratio, it was necessary to estimate the total energy output over entire lifetime of the considered plant. It was found on the basis of average plant load factor and average life of coal power plants in India. In the year 1999-2000 the nation wide average plant load factor (PLF) was 0.64 (5606 hrs./year load duration). For financial and technical analyses, usually a life of 40 years is considered for coal power plants in India. Using the same values, calculations of EYR have been done as shown in the following steps:

Annual electricity output = 16.35 PJ_{el}
Lifetime electricity output (for 40 yrs. life) = 653.9 PJ_{el}
Primary energy equivalent of lifetime electricity output = 1981.55 $PJ_{primary}$
Cumulative Energy Demand (for production of plant) = 3522.9 $TJ_{primary}$
Primary Energy Yield Ratio ($EYR_{primary}$) = 562.4
Physical Energy Yield Ratio ($EYR_{physical}$) = 185.6

It is important to kept in mind while comparing results with other studies that these values are based on only the CED_P only and not based on CED_{total} which included energy demands during operation, maintenance and disposal also. With all these values included, the EYR figure will come down. Furthermore, if the primary energy consumption through consumption of coal in the utilization stage is considered, the value of $EYR_{primary}$ becomes slightly less than unity and $EYR_{physical}$ approached the plant slightly lower value than the efficiency figure. With this approach both the EYRs become less than unity because as per the law of energy conservation energy output cannot be more than energy consumed. Hence, with the energy of coal considered, there is no energy pay back in real terms and from the primary energy perspective, any amount of energy consumed is in fact energy lost for ever.

Results of other studies

Energy analysis of a hard coal power plant was conducted with relatively more details jointly by few researchers of Germany [Heithoff 1998]. Hard coal power plants considered in this study were the state of the art systems in the field of thermal power generation. Capacity of a typical plant is 509 MW (for net output) with a net efficiency of 43%. For comparison with our own study, the plant has been assumed to be located in India. Operating conditions and related data for the plant have been modified as per Indian conditions (mentioned in the analysis of Indian power plant in previous section).

Cumulative energy demand for the plant has been calculated with a break-up for production(CED_P), utilisation(CED_U) and disposal(CED_D) of the plant. In a total figure for CED_P of 2635 TJ for the entire plant, the CED_P of the structural components amounts to 677 TJ. Within this section about 47% belong to the component of steel in the building. The CED_P for the machine parts comes to a total of 1152 TJ, where boiler unit (50%) and flue gas purification system (19%) hold the bigger share. The CED_P of the electro-technical parts (222TJ) is about 8% of the total CED_P of the plant. These figures when extrapolated for comparison with our own results, were found to be in agreement. Besides CED_P, not only usage of operational materials and energy, such as electricity consumption on the building site, fuel oil for trial runs of several machines and lubricants, but also energy consumption for transportation and excavation were taken into account in the German study and were found to have a share of 22% (584 MJ) in the total CED_P of 2635 TJ.

To estimate the share of energy demand through fuel consumption in the CED_{Total}, again the efficiency and plant life figures were used. The energy demand for the utilisation phase that is the period in which power is generated from the plant is found to be 5.9 PJ without considering the energy demand due to hard coal. Whereas, the total energy demand in utilisation phase with hard coal taken into consideration increases to 1014.8 PJ, increasing the grand total of CED from 8.2PJ to 1023PJ. This indicates that the total CED_U is almost equal to the total cumulated energy demand and other energy demands CED_P, CED_U (non-fuel), CED_D have a share of just about 1%. Hence, it is recommended that if primary energy consumption through fuel is considered, the CED through other components can even be neglected in case of such plants.

The CED_P in case of Indian power plant represented in specific terms was found to be about 4.19 TJ/MW_{el} as compared to 5.17 TJ/MW_{el} in case of the German study. Another study [Schaefer 1992] shows resembling range of results with variation from 2.9 TJ/MW_{el} to 9.0 TJ/MW_{el} depending upon size and technology used in the plant.

Environmental Analysis

Based on the conclusion that the share of materials and manufacturing processes is negligible in the total CED of the plant (with the CED of fuel included) that approach for the environmental analysis of coal power plants has been simplified. The share of materials and manufacturing processes in total cumulative greenhouse effect (CGHE) is therefore also neglected and for this analysis therefore, emissions due to burning of fuel has only been considered. Bansal N. in India had found that that the CO_2 emissions per unit energy delivered by a coal power plant are varying from 0.73 to 0.92kg CO_2/kWh_{el} [Bansal 1998]. Variation is there in this value due to change in composition of coal and plant efficiency that are plant specific.

The 509 MW plant considered in its lifetime with a plant load factor of 0.64 gives an output of 114.146 TWh of electricity. Using the emission coefficient for coal power plant, a total emission equivalent to 105.01 x 10^9 kg in its lifetime. The emission coefficient thus comes out to be 0.71 kg CO_2/kWh_{el} . In some other similar studies, emission coefficients ranging from 0.89 kg CO_2/kWh_{el} to 1.2 kg CO_2/kWh_{el} have been observed. This value in fact, largely depends upon the operating parameters of the plants.

4.3 Dynamic Energy Analysis

The practice of energy analysis has been extended in the for m of dynamic energy analysis as described in chapter 3 earlier. Basic requirement for this work was value of cumulative energy demand for each of the technologies under consideration. These values have been obtained through our own calculations (as covered in previous sections of this chapter) and on the basis of other studies as described below.

4.3.1 Cumulative Energy Demand for Power Plants of Considered Technologies

International Energy Agency has published range of LCA parameters of different power generation technologies in one research report on hydro power [IEA 2000]. This study presents Energy Yield Ratios of various technologies for different part of the world including Asia. The drawback with the information available in this report is that important details about considered life of power plants and annual energy output have not been mentioned that are required to find Cumulative Energy Demand from the Energy Yield Ratios. However, this results related to Energy Yield Ratio, in this study have been found in agreement with the results found in by own calculations as mentioned in previous sections. Besides, few years back, in one study of photovoltaic power generation in Germany, a comprehensive coverage of accumulated energy in different power plants was presented covering power plants of various technologies and plant sizes [Schaefer 1992]. Values of Cumulative Energy Demand found through our own study match with the values mentioned in this study and hence for other plants values of CED have been taken from this work for calculations of dynamic analysis in the next part. Using the Energy Yield Ratios mentioned in the IEA study, and considering the plant lifetime related information commonly used in other works, CEDs have also been calculated and not much variation has been found with this study.

Some of the referred studies have even given the share of various fuels in the total CED. In case of PV power plants the share of electricity has been found to vary from nearly 70% [Schaefer 1992] to about 90% [Völlmecke 2000] ,[Guerzenich 2001]. The share of electricity in wind energy converters has been found to be about 30% [Hagedorn 1992]. In case of coal power plant this share is quoted to be about 25% [Heithoff 1998].

Table 4.8 presents the range of CED related information found and calculated through these studies. Few other studies like [Völlmecke 2000] and [Krohn 1997] were also consulted and found to be in tune with other studies taken as references. The last column indicates the values chosen for use in the dynamic analysis calculations done in the next section of this chapter. These values have been taken corresponding to the preferred plant sizes in India and therefore do not have any fixed co-relation with the range of CED. However, sensitivity analysis has been done to find the effect of variation in CED on results of dynamic analysis. Values given in table 4.9 are also rounded off from exact values as mentioned in parent studies because these are only to represent the range of CED.

Table 4.9: Cumulative Energy Demand of various technologies

Technology	$CED_{max.}$ (MWh/MW)	CED_{min} (MWh/MW)	CED_{chosen} (MWh/MW)
Photovoltaic (mono-crystalline)	20500	10000	12500
Photovoltaic (poly-crystalline)	20000	8000	9500
Photovoltaic (amorphous)	13300	5000	6500
Wind (small)	4700	2000	2500
Wind (large)	2600	1000	1500
Hydro (large)	10000	3500	6500
Hydro (small)	10000	3500	6000
Coal (advanced)	4000	1200	1200
Coal (moderate)	3000	800	1000
Coal (basic)	2500	600	800
Natural Gas (combined cycle)	3000	700	900
Natural gas (simple cycle)	2000	400	500

4.3.2 Calculation of Maximum Growth Rates

As described in section 3.3.1, results of energy analysis have been extended to find maximum allowable growth rate for each considered technology. In the methodology, the method of calculating maximum growth rate using the new developed dynamic analysis approach has been explained for both the cases. One, named as case-1 in section 3.3.2, in which entire energy output from any technology can be reinvested for capacity expansion if it is the most preferred technology. In the other case, called case-2, only a fraction of energy output is considered for reinvestment for capacity expansion as in India each set of technologies is managed by separate ministry or department. During recent past few years about 20% of the annual national budget has been allocated for power generation capacity expansion. Following the same approach, a maximum of 20% of the national power output has been considered for reinvestment for capacity expansion and this ceiling has been uniformly applied on each technology. It means, a maximum 20% of the power output in any year from every technology has been kept in transient equations to find the maximum growth rate of each technology. Investigation of equation 3.32 shows that CED, annual energy output 'en_k' and construction time 't_c' (gestation period) of power plants are main governing parameters for determining the maximum growth rate *'a'* besides the reinvestment factor *'x'*. Table 4.10, shows maximum growth rate corresponding to average construction time for each plant for case-1 and case-2 along with values of other related parameters as mentioned above.

Table 4.10: Maximum Growth Rates Obtained Through Dynamic Energy Analysis

Technology	$CED_{electrical}$ GJ/MW	Annual output GJ_{el}/MW	Average plant construction time (years)	Maximum growth rate in % (case-1)	Maximum growth rate with 20% re-investment factor (case-2)
Photovoltaic (mono-crystalline)	36000	4730	1	31.9%	7.24%
Photovoltaic (poly-crystalline)	27360	4730	1	40.2%	9.42%
Photovoltaic (amorphous)	18720	4730	1	54.3%	13.5%
Wind (small)	2700	12614	0.6	444%	216.7%
Wind (large)	1620	12614	1	314.6%	169.6%
Hydro (large)	11700	18921	7	24.7%	9.35%
Hydro (small)	10800	23652	3	64.1%	25.8%
Coal (advanced)	2160	20183	4	83.0%	46.2%
Coal (moderate)	1800	20183	4	87.4%	50.1%
Coal (basic)	1440	20183	4	92.9%	54.9%
Natural Gas (combined cycle)	1620	20183	3	120%	69.8%
Natural gas (simple cycle)	900	20183	2	208.8%	131.3%

There is a difference in the values of CED given in the table 4.10 with the values given in table 4.9. It is due to the fact that for the purpose of dynamic analysis, the share of electricity alone in the CED was of use. This has been explained in section 3.3.1 that the dynamic balance has been done for the supply and demand of electricity only and not for total energy demand and supply which also includes other forms of energy. For this purpose CED_{Total} was converted into $CED_{electrical}$ details of which have been given in appendix-5 along with other information about calculation of maximum growth rates for various technologies.

Chapter-5

INDIAN POWER SECTOR: THE REFERENCE ENERGY SYSTEM

5.1 Background

Techno-economic aspects of power generation can be grouped under three broad headings: power or energy demand, availability of energy resources, and conversion technologies. Issues like market price of power, fuel price etc. though are individually important, have been linked in this study with any one or combination of above three categories. Attempts have been made in the following sections to present a comprehensive view of almost all the aspects of power generation including development of a perspective view of the Indian Energy Sector with special focus on power generation. Modelling with MARKAL requires establishment of relationships between technologies, activities and energy flows from primary energy stage up to the end-use through different intermediate stages such as refining, transportation/transmission, conversion. These co-relationships defined through process parameters & constraints have also been covered in their respective sub-sections of this chapter.

For this study, the Indian power sector has been taken as the reference energy system. Power sector since beginning was lacking in co-ordinated and well directed planning and operation. Power Sector Reforms were initiated by the Government of India with the liberalisation process set in motion in 1991. The first decision that was taken was to allow private investments in power generation for public utility. Due to the bankruptcy of most state electricity boards, the first phase of reforms could not reap much fruits as there was no assurance of payments to power producers. In the second phase, and specifically after setting up of Central Electricity Regulatory Commission in 1998, both central and state government agencies are functioning with growing effectiveness. Over a period, now much improvement in power sector is envisaged as critical issues like privatisation of distribution sector, are also getting attention. In this changing environment, energy policies and related research are going to play a vital role by giving proper directions to the improvements in the energy sector.

5.2 Energy Demand: Trends and Projections

Energy demand that is the most important figure for any energy planning activity, is specified in two ways. One is the commercial energy demand which includes demand of energy through all marketable sources of energy e.g. coal, oil, gas, nuclear fuel. Second, power (electricity) demand only that is more commonly recognised as electricity demand. Though the scope of this study is confined to the power sector, brief commentary of the other forms of commercial energy demands has also been given for presenting perspective view of the entire energy scenario.

5.2.1 Commercial Energy Demand

The total commercial energy availability in India increased from nearly 4286 PJ (100 MTOE) in early 1980s to around 7954 PJ (190 MTOE) by the early 1990s. This implies an annual growth at the rate of 6.9%. Availability of commercial energy reached 11890 PJ (284 MTOE) by 1998-1999 growing at a lower pace of 5% per annum [CMIE 2000]. About one third of the gross availability of commercial energy was lost in conversion, transmission and distribution during past few years. The ratio of loss to gross availability has been increasing from about 25% in 1980-81 to 33% in 1997-98. Thus, the final or net availability of commercial energy is estimated to have increased from about 2889 PJ (69 MTOE) in 1980-81 to about 5233 PJ (125 MTOE) in early 1990s at an annual growth rate of 6.1%. It grew up to 7787 PJ (186 MTOE) in 1997-98 at a growth rate of 5.5% per annum. Figure 5.1(a) shows the gross and net availability of commercial energy in India.

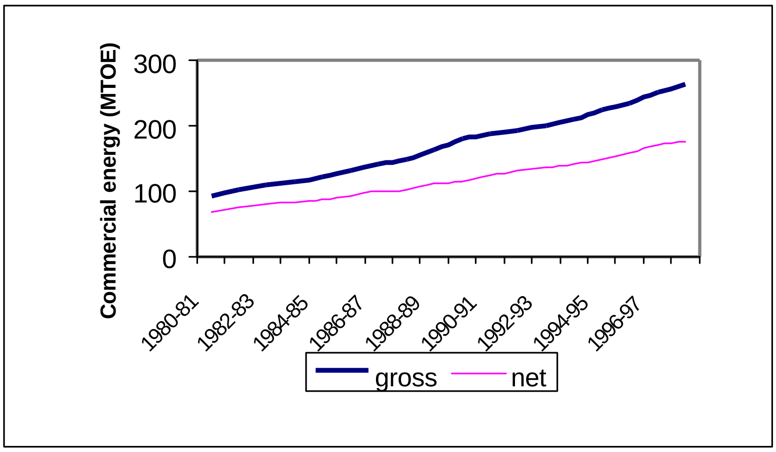


Figure 5.1(a): Trend of Availability of Gross and Net Commercial Energy in India

Commercial energy consumption can be divided into following five different sectors namely Agriculture, Residential, Industry, Transport, Others or Commercial. Figure 5.1(b) shows share of these sectors into total commercial energy consumption in the year 1997-98. Non-commercial sources of energy such as firewood, contribute towards a considerable portion of gross energy demand in the country. Percentage share of non-commercial energy is continuously decreasing with time which is yet another reason for increase in commercial energy demand. The share of commercial energy was just 26% in 1950-51 that has increased to more than 70% in late 1990s [TEDDY 2000].

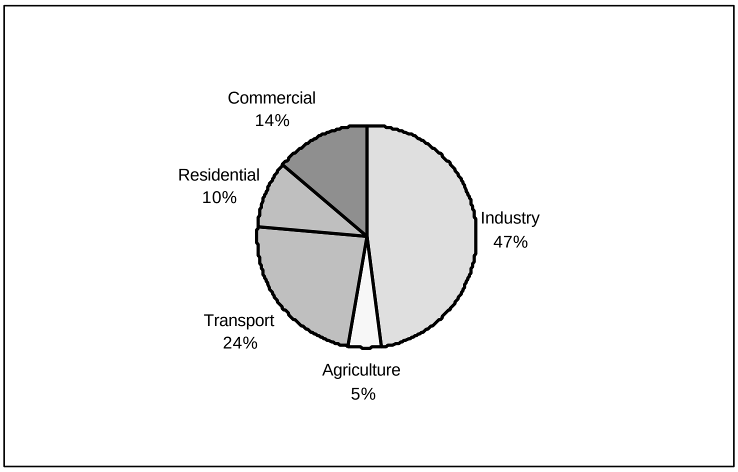


Figure – 5.1(b) Sector wise break-up of commercial energy utilisation in year 1997-98

5.2.2 Aggregate Electricity Demand

Similar to the commercial energy demand, electricity demand has also been divided into five categories namely, agriculture, industry, residential, transport and commercial. Each of these categories or sectors of economy, have typical growth trend of energy demand. They also have different fuel mixes and tariffs of electricity are also different for various types of consumers belonging to these sectors. Demand of electricity in India, has ever been more then the supply leading to a shortage of power. In the year 1998-99, there was an average power shortage of 8-10% and shortage during peak load hours was about 20% in different months of the year. Shortage of power has shown an increase over past few years as the growth in demand has been at a faster rate then the generation. The Central Electricity Authority through the Fifteenth Electric Power Survey for India, had projected an energy demand of 570 TWh in the year 2001-02. It had also projected that this demand would go up to 782 TWh by the year 2006-07. Peak load is estimated to reach 95757 MW in 2001-02 and 130944 MW in 2006-07 and 176650 MW in 2011-12 [CMIE 2000].

The Sixteenth Electric Power Survey completed in the end of year 2000, however, has scaled down the estimations of fifteenth survey by about 10%, in view of the fact that the government does not expect an much economic changes till the end of the year 2010. The estimated growth of power demand during the new decade has been scaled down to 6.13% from 6.5%. According to the sixteenth electric power survey, the peak demand at the end of ninth and tenth five year plan periods (i.e. years 2001-2002 and 2006-2007 respectively) will be 84500 MW and 118000 MW, respectively. The actual energy requirement is also projected to be lower at 535GWh and 782GWh, respectively. Year wise demand of electricity from public utilities has been shown in Appendix-6.

Table 5.1: Power Demand Projections for India

	Fifteenth Electric Power Survey	Sixteenth Electric Power Survey	Own Trend projection using equation 5.1
Peak load in 2001-02	95757 MW	84500 MW	____
Peak load in 2006-07	130944 MW	118000 MW	____
Peak demand in 2011-12	176650 MW	____	____
Power demand in 2001-02	570 TWh	535 TWh	543 TWh
Power demand in 2006-07	782 TWh	700 TWh	705 TWh

Source of data: [CMIE 2000]

As MARKAL requires energy demand figures for the period under study, it was found necessary to project these figures of demand to find the desired values. The demand trend line shown in figure 5.2 has been drawn using the demand figures of past 20 years and projections of the sixteenth power survey.

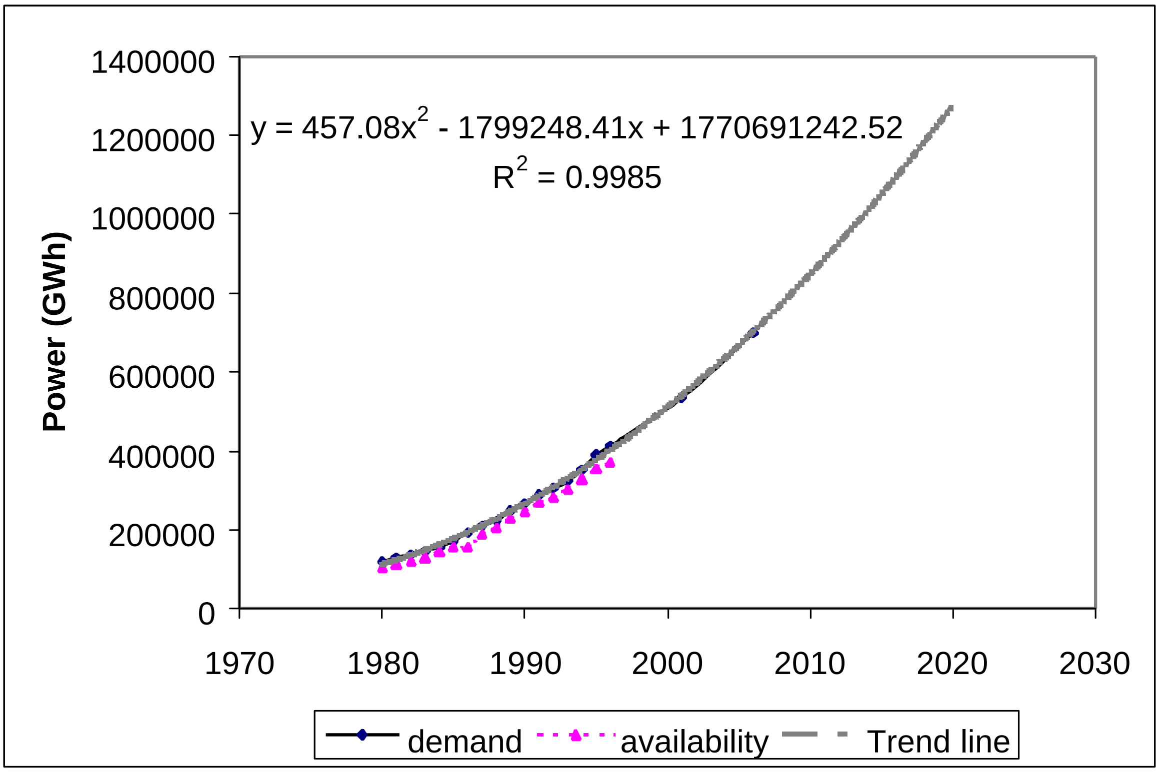


Figure 5.2: Aggregate Power Demand and Power Supplied in India

Equation 5.1 given below represents the inserted trend line using the least square method. The same relationship has been used to estimate power demand in year 2005, 2010, 2015 and 2020 for use in the MARKAL analysis.

In this equation for finding power demand for in any year (after 1980), the year has to be expressed as such as ‘n’:

$$Demand_n = 457.08n^2 - 1799248.41 * n + 1770691242.52 \tag{5.1}$$

Sector-wise Electricity Demand

Agriculture Sector

Agriculture sector is the largest sector of Indian economy. In this sector, land preparation and irrigation are two major agriculture related operations where energy is extensively used. Agriculture is a seasonal industry and therefore, the demand for energy fluctuates throughout the year. Oil and electricity are two major sources of energy in this sector. During 1997-1998 and 1998-1999, oil contributed towards about 64% and share of electricity is about 36% in the total energy demand for agriculture. Notable fact about these shares is that the total demands for oil and electricity for agriculture have increased over the years but their relative percentages are almost the same for past many years unlike other sectors [TEDDY 2000]. Increase in energy demand in agriculture sector can be attributed to increasing electrification of villages resulting into replacement of labour intensive methods by machine operated methods for various activities. The electricity consumption in agriculture sector was just 15201 GWh in 1981, in 1991 it rose to 58788 GWh and in 1994-95 it further grew to 79301 GWh. The share of agriculture sector in total electricity use in the year 1996-97 was 30.9%. Appendix-7 shows year wise energy consumption in the agriculture sector and its share (along with other sectors) in total power consumption of the country.

Trend analysis reveals that electricity consumption in agriculture sector expanded at a rate of about 13% during 1971-1991. It has been the fastest growing sector for power demand. During the 1990s growth rate was close to 9%. Besides planned expansion of rural electrification, unplanned subsidies on electricity tariffs for agriculture sector and absence of metering in this sector of many states have given rise to number of electric pump sets for irrigation and inefficient use of electricity consumption in this sector.

Industrial Sector

The industrial sector is the largest consumer of electricity in the country. The industrial sector consumes about 50% of total commercial energy produced in the country. Growth rate of the industrial sector was about 6.6% in 1996-97 as compared to the highest growth rate of 12.8% achieved in 1995-96 as an exception. Besides use of electricity from public utilities, industrial sector has an almost equal consumption of electricity through captive generation of power. Oil, naphtha, high-speed diesel, light diesel oil, LPG and coal as other sources of energy in this sector. Table 5.2 shows share of electricity in industrial commercial energy demand in the year 1995-96.

Table 5.2: Share of different energy sources in industrial energy demand in year 1995-96

Form of energy	Unit	Consumption
Electricity from utilities	TWh	34
Captive electricity	TWh	32
Fuel oil	Thousand tons	4836
Naptha	Thousand tons	3669
HSD	Thousand tons	2386
Light diesel oil	Thousand tons	700
LPG	Thousand tons	737
Coal	Million tons	96

Source: [CMIE 2000]

Residential Sector

Consumption of electricity and commercial energy as a whole is increasing in the domestic or residential sector every year due to several reasons. There has been a steady shift from non-commercial to commercial sources of energy. Within commercial energy sources also, there has been a shifting. Access to electricity, coupled with higher disposable income and increased number of electric households, are few of those reasons that cause this change. Between the years 1980-81 and 1990-91, the consumption of electricity grew at an annual rate of 13.2% against 9% in 1970s. It was because of faster pace of electrification of villages. During the first half of 1990s the growth rate declined to 10.6% per annum. In the year 1980 the demand for electricity was just 9.25 TWh which had grew to nearly 48 GWh in 1994-95 along with consumption of 6.96 million tonnes of kerosene and 2.76 million tonnes of LPG. There are two major factors governing the demand of electricity and other sources of energy in domestic sector. One is population increase and other is change in per capita energy consumption pattern. Increasing rural electrification and gradual removal of subsidies from LPG and kerosene are have also contributed towards increase in electricity demand. Since 1990-91, there has not been much change in per capita consumption of kerosene and since 1994-95, per capita consumption of cooking gas (LPG) is also increasing but at a lower pace as compared to the growth in demand of electricity.

Transport Sector

The total commercial energy consumption in the transport sector grew at a sluggish rate of 3.1% annually between 1970-1980. In the next decade the annual growth rate was 4.9% which further increased to 5.6% from 1990 to1998. This slow increase has been due to shift of major transport activity from rail to road and from public transport to personalised transport. Electricity consumption in transport sector is mainly due to the transportation by electric rails. The length of electrified network has increased from 3706 km. in 1970-71 to 13490 km. in 1998 accounting for about 23% of the rain route. The planning commission of India has recommended an accelerated plan for electrification of railways that will increase the electricity demand in this sector [TEDDY 2000].

Commercial sector

Details of the electricity consumption in commercial sector are not usually available separately. Rather, the balance of electricity consumption after accounting for the above four sectors is assigned to this sector. This share is also covered under the head ‘OTHERS’ in some studies. The compounded average rate of growth (CARG) of power demand in this sector is found to be nearly 8.2% since 1980, however, during the last decade an average annual growth of 6.8% has been observed in this sector. Growth of power demand in this sector has a close relationship with the GDP growth rate. Consumption of power in offices, markets, street lighting etc. are few major contributors in this sector.

5.3 Energy Supply

5.3.1 Electricity supply

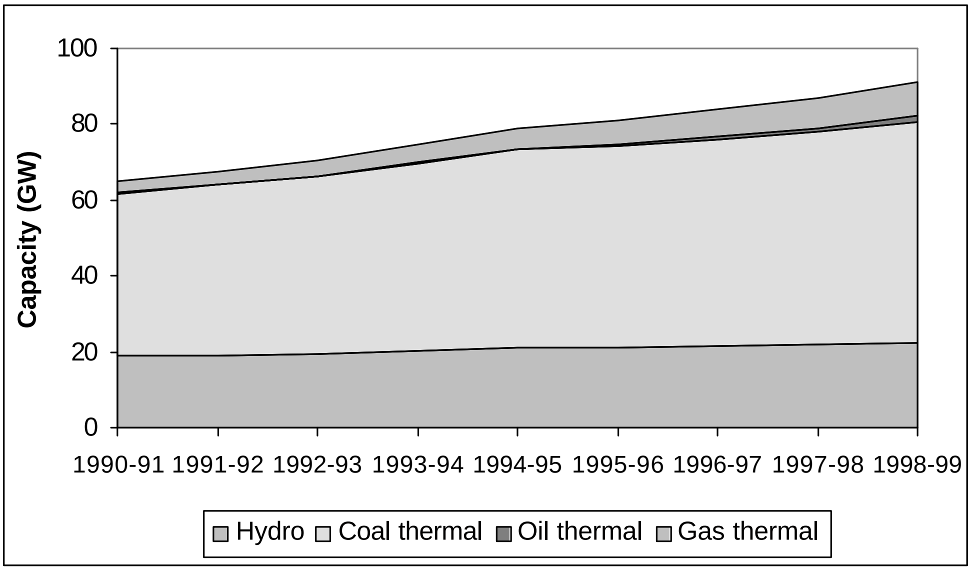
Installed capacity

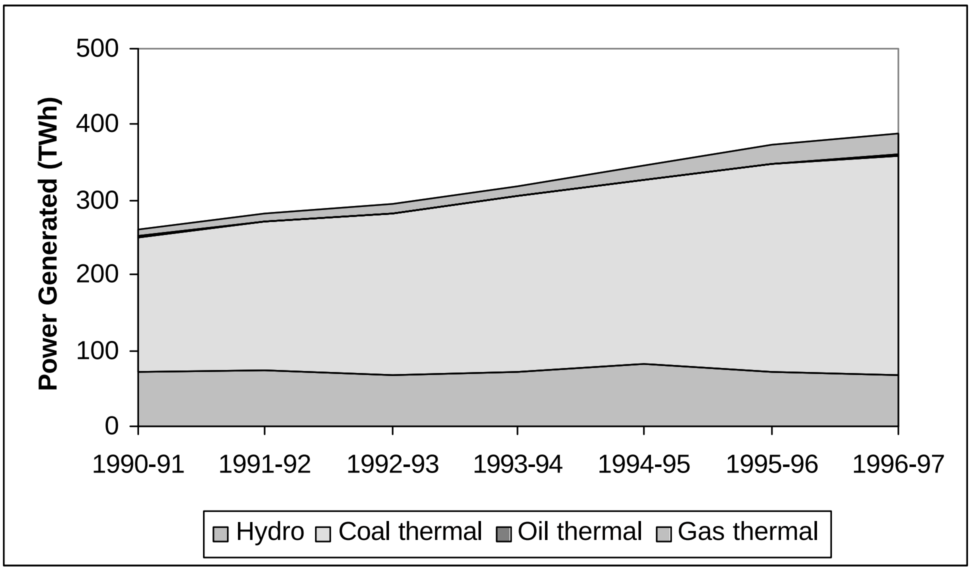
As of March 1999, total electricity generation capacity in the country stood at 105,300 MW. This includes 93,249 MW of capacity in the form of public utilities and around 12,000 MW as captive power generation capacity. The state sector owned 63% of the capacity in the utilities while the central sector accounted for remaining 37%. Within the utilities, 73.5% share in the power generation capacity was with thermal power plants and about 24% with hydro power plants. Nuclear power and renewable energy based power plants jointly have a share close to 2.5%. Appendix-8 shows share of different technologies in the total power generation capacity of India since 1980-81.

The power generation capacity increased at a rate of 12% per annum during the 1960s. The period of 1970s recorded a decline in the growth rate to 7.5% per annum. In the 1980s growth of 8.1% was observed but it again dipped in 1990s. During the period 1990-91 to 1998-99, power generation capacity growth of only 4.4% per annum has been achieved. These growth rates have been much lower than their respective targets set by the planning commission of India, during the past decade.

Power Generation

Growth of electricity generation in India has been almost in tandem with the trend of capacity expansion. During the 1960s electricity generation increased at an annual growth rate of 13%, in 1970s it was 7%, in 1980s 12% and in 1990s 6.8% growth in generation has been achieved. In 1990s though the growth in capacity has been less then 5%, more growth in generation is there mainly due to increase in plant load factor. On an average, there has been an increase of 1% per annum in the availability of thermal power plants. Appendix-8 besides power generation capacity also shows details of generation of electricity by various technologies since 1980-81. Figure 5.3 shows trend of increase in power generation capacity and power generation through various technologies.



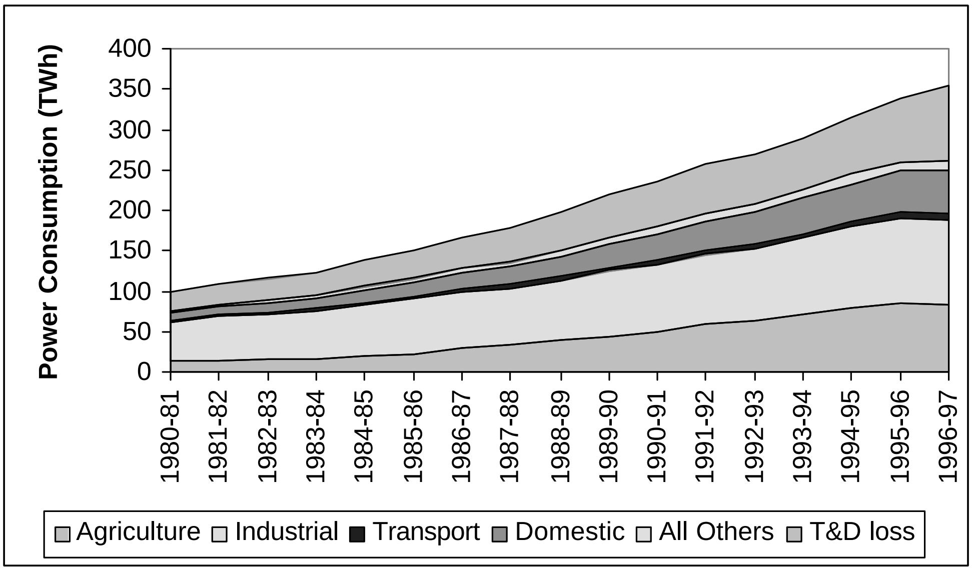


*Oil thermal includes diesel power plants working with wind power plants

Figure 5.3: Break-up of power generation capacity and generation from various technologies

Transmission & Distribution (T&D) Losses

The transmission & distribution losses amounted for more then 20% of the available power during the period 1990-1999. These losses were below 20% in the previous decade. There was a dip in T&D losses to 19.8% in the year 1992-93 and it peaked at 23% in 1996-97. In few states like Orissa, T&D losses almost touched the mark of 50% losses [CEA 2000]. In this study, average figure about the T&D losses i.e. 20% is considered. However, in regional level planning or decentralised planning studies, state wise or local figures for losses should be taken. Year wise growth of T&D losses are shown in figure 5.4 along with the trend of sector wise power consumption .



Source [CMIE 2000]

Figure 5.4: Sector-wise consumption (in TWh) of available power including T&D losses

5.3.2 Primary Energy Supply Options for Electricity Generation

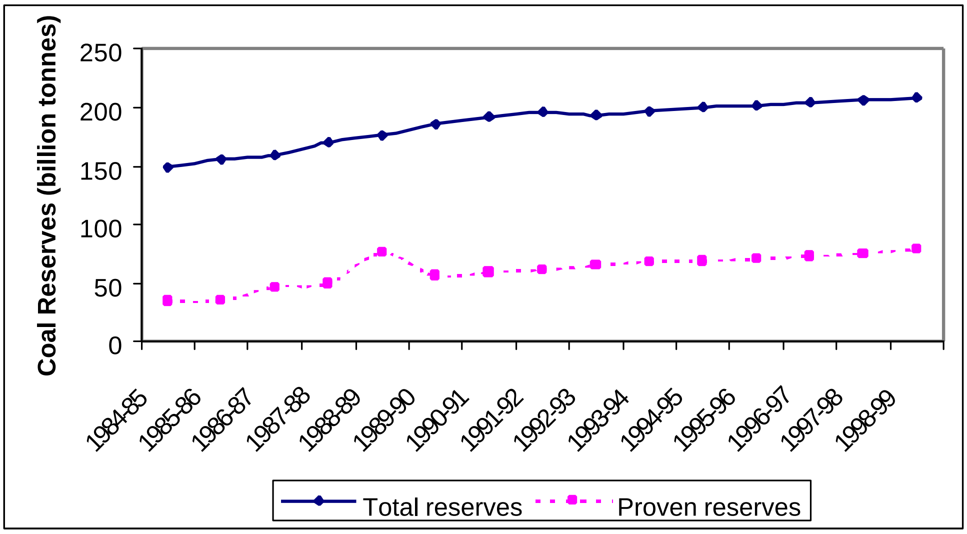
Primary energy requirement for power generation is met through conventional as well as non-conventional sources of energy. The term primary energy here refers to the naturally available from of energy that may be in the form of coal, oil, gas, nuclear fuel or renewable energy such as hydro power, wind power, solar irradiation power etc. The commentary on these has been divided in two sub-sections: Fossil Fuels and Renewable Energy.

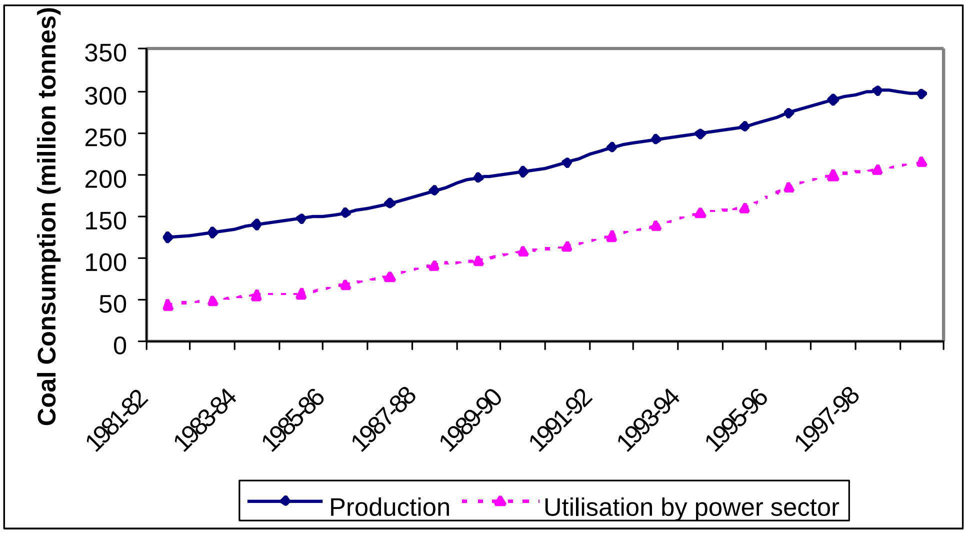
Fossil Fuel Availability

Coal

The Geological Survey of India has estimated India's proven coal reserves to be 79106 million tonnes and total coal reserves to be 208751 million tonnes up to a depth of 1200 meters. As a result, coal is the most important source of primary energy in India. Total coal production since 1980 has increased at an average rate of 5.24%, whether coal utilisation in power sector has increased at 9.83% per year. Figure 5.5 shows the trend of amount of total coal reserves, proven coal reserves in India along with the trends of production of coal and coal-utilisation for power sector.

Phased liberalisation of the coal sector started in 1992 with permitting private sector investment in coal mining. In the second phase of deregulation in 1996, prices of coking coal and superior quality grades (grades A, B, C) were deregulated followed by de-regulating prices of coal of grade-D (which is most widely used for power generation) in 1997. With effect from January 2000, coal producing companies in India are free to decide prices of coal of lower quality grades E, F, and G according to market forces like higher grade coal. In Appendix-9, details about properties of different grades of coal are given.



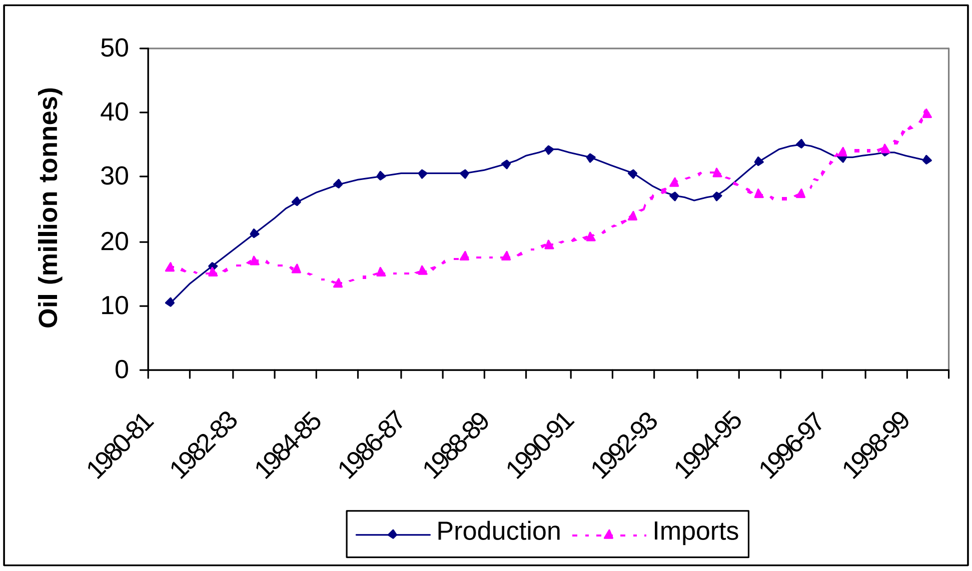


Source: [CMIE 2000]

Figure 5.5: Coal reserves, Production and Utilisation by Power Sector

Oil

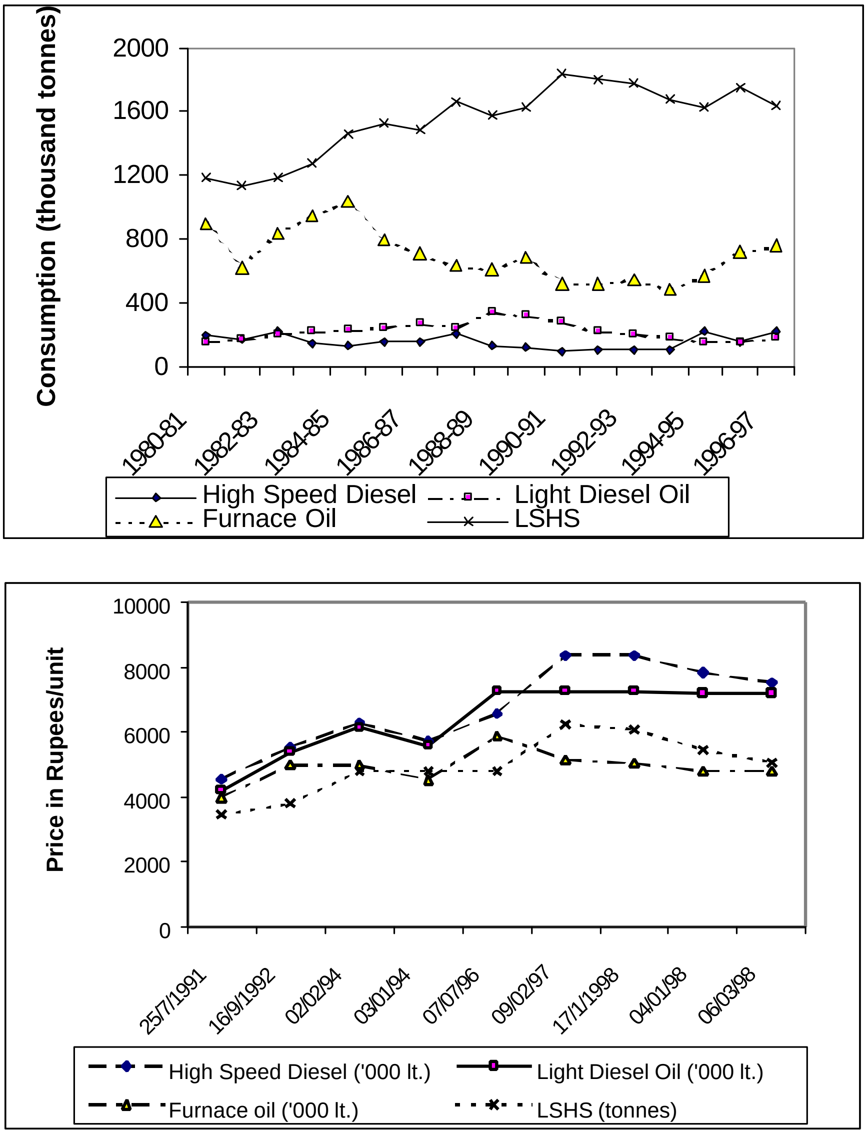
Unlike coal reserves, proven crude oil reserves in India are now on a decline after reaching the peak in 1991. This figure also shows aggregate production of crude oil from all oil fields that peaked in 1995-96. Thereafter there is a decline in production and as a result the share of domestic crude in total crude consumption in the country is also declining. Appendix-10 and figure 5.6 show availability of crude in the country through indigenous sources and imports.



Source: [CMIE 2000]

Figure 5.6: Availability of Crude Oil in India

Crude oil as such directly is not used in the power sector. It is first refined in refineries to yield different distillates. Only four distillates of crude oil namely, High Speed Diesel (HSD), Light Diesel Oil, Furnace Oil and Low Sulphur Heavy Stock (LSHS) are used for power generation purpose. Out of these four, furnace oil and LSHS are most widely used in this sector. Appendix-11 shows consumption of these distillates in the power sector in different years. Since LSHS contributes towards about 60% of total oil consumption in power sector, average properties like calorific value, and costs of LSHS are used in calculations as reference values. However, the sensitivity analysis shows no significant variation in the results of the MARKAL analysis due to use of corresponding values of other three products. Instead of considering retail prices, ex-storage prices are considered as the power sector is a bulk consumer and will not be covered under retail prices. Appendix-11 also shows prices of these petroleum products in India during past few years. Prices of petroleum products in India, are controlled through the Administered Price Mechanism (APM) that constitutes cost-plus pricing and cross-subsidies on certain products. Therefore, in the country, prices of petroleum products are neither actual prices nor free market prices. The government has now started dismantling the APM, 1998-2002 is the transition period for this change. As per the recommendations of the dismantling mechanism developed by the National Council for Applied Economic Research (NCAER), the prices of fuel oil, LSHS and naphtha can now be fixed at market price unlike prices of HSD, LPG and ATF (aviation turbine fuel) that will be kept at parity with imports [MoP 1999]. Therefore, in case of fuel oil prices relevant for power generation, a price inflation equal to the national inflation rate has been considered in this study on the base year price. Although the prices of petroleum products have shown a different trend so far, but this trend will not be able to provide any feedback for the future trend as is clear from figure 5.7.

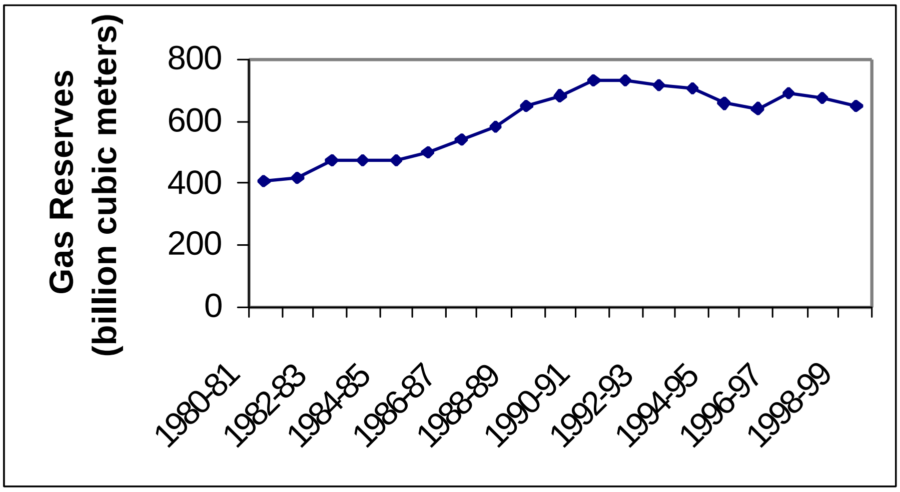


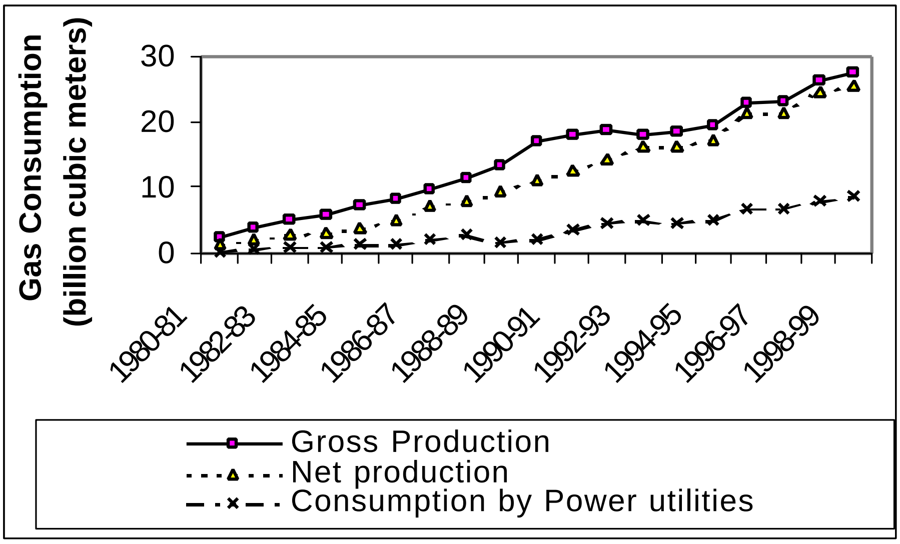
Source: [CMIE 2000], (1Euro = Approx. 40 Rupees in year 2000)

Figure 5.7: Consumption and Prices of oil products used for power generation

Natural Gas

Similar to the crude oil reserves, proven natural gas reserves in India have also shown a decline after peaking in 1992. The advancements in gas utilisation technologies as well as environmental concerns have resulted into a rise in the demand of gas. Natural gas accounted for about 8% of the country's commercial energy consumption in year 1998. Figure 5.8 shows amount of domestic gas reserves and the production of gas that has been increasing at an average annual rate of about 6% per year. Few major pipeline projects are under execution for facilitating transportation of gas within country and some other are in negotiation stage from gulf countries, that will ensure availability of gas in all major locations.





Source: [CMIE 2000]

Figure 5.8: Proven Reserves and Consumption of Natural Gas in India

In the dismantling process of APM as explained in the case of crude oil, pricing policy of gas is also undergoing major change. The deregulation of gas pricing is taken to establish a rational market-related pricing framework for the end-users. With effect from October 1, 1997 up to March 2000, the consumer price of gas was increased in phases to land up at 100% parity with fuel oil prices. Under these conditions, similar to the price of oil, price of natural gas is also considered to increase at the rate equal to the national average inflation rate. However, to cover the possibility of reduction or slower increase in the prices of gas as compared to other fuels due to possible exploration of new reserves or cheaper imports, sensitivity analysis has been done and the effects are discussed in chapter 8.

The variation in availability of natural gas recent past years has been shown in Appendix-12. In this study the prices considered are with respect to the gas having calorific value 42000 kJ per cubic metre, as linked with the conditions in the APM [TEDDY 2000].

Nuclear Fuel

Nuclear fuels, over the years have emerged as single largest promising solution to the problems of depleting reserves and environmental degradation, world wide. Vast Indian reserves of thorium promise to support the fuel requirement for over 350000 MW capacity for more than 300 years. There are about 78000 tonnes of uranium and 518000 tonnes of thorium reserves in India. The nuclear power corporation has made an ambitious plan to utilise uranium through Pressurised Heavy Water Reactors (PHWR) and Fast Breeder Reactor (FBR) systems to have a large power generation capacity in coming years. Further, it has also been planned to utilise Fast Breeder Reactors (FBR) through Plutonium as fuel and Thorium as blanket for breeding U_{233}. In the next stage of planning, breeder reactors are planned to be used with U_{233} as fuel and Thorium as blanket [NPC 1999].

Renewable Energy Potentials

India has a substantial potential for almost all types of renewable energy options. As per the estimates of the Ministry of Non-Conventional Energy Sources (MNES), estimated potentials of renewable energy in India have been shown in Table 5.3. Values of these maximum potentials have been used to assign upper bounds for power generation capacities of considered technologies in the MARKAL analysis of this work.

Table 5.3: Estimated Renewable Energy Potentials in India

Source/System	Approximate potential
Technologies considered in this study*	
Solar Energy	20 MW/km^2
Wind Energy	20000 MW
Large Hydro Power	84000 MW
Small Hydro Power (up to 15 MW capacity)	10000 MW
Other renewable energy technologies	
Bio-gas plants	12 million (nos.)
Improved wood-stoves	120 million (nos.)
Bio-mass	17000 MW
Ocean Energy	50000 MW
Energy from urban, municipal & industrial waste	1700 MW

Source: [MNES 1998] ** Criteria for selection of technologies explained at end of section 5.4.2*

Values of potentials of wind, large hydro and small hydro power shown in table above are economic potentials and for other technologies seem to be technical potentials.

Details about the operating conditions and performance of these systems have been discussed in the section 5.3.2. One major difference while dealing with renewable energy systems as compared with non-renewable energy systems, is that the plant utilisation is not in control of user-agency. It mainly depends upon the availability of energy source e.g. radiation, wind, water, which are linked with the climatic conditions. In contrast to this, availability of non-renewable energy systems is almost independent of the climatic conditions and plants can operate at relatively more stable utilisation factor throughout the year.

5.4 Energy Conversion Technologies

Host of energy conversion technologies are being used in different parts of the world and in India for power generation. Broadly these technologies are classified under two categories namely, conventional and non-conventional technologies. Another way of classifying them is in categories renewable energy technologies and non-renewable energy technologies. The later classification is often preferred as it directly refers to the depletable or non-depletable kind of energy source and hence has also been adopted for coverage of technologies in this study as given below. Attempts have been made to briefly cover almost all commercially available technologies in this section. Justifications for considering selected technologies have been given along with brief comments on their technical and financial parameters used in this work. Values of various parameters mentioned in these sections are the values that have been used as reference values in the MARKAL model. However, major possibilities of variation in these values has been discussed in the sensitivity analysis chapter.

5.4.1 Non – Renewable Energy Based Technologies

Conventional Coal Thermal Power Plants

Stoker based coal firing has been the dominant technology for electricity generation in India so far. It is currently used for more than 70% of coal based power generation systems. Thermal performance of steam turbines has slowly increased over the years, mainly by adopting progressively higher steam conditions. Due to shortage of power generation capacity and also due to shortage of money for instaling many new plants, the Indian government, through the power sector reforms, has decided to go for retrofitting of old power plants, instead of retiring them at the end of life. Therefore, all existing power plants have been considered to be available throughout the period of this study. Initial cost or investment cost for conventional coal power plants also has some variation from plant to plant. Details taken from the project reports of Suratgarh Thermal Power Plant (RSEB), and Kahalgaon Thermal Power Plant (NTPC), have been the basis of most parameters for this technology in his work. Following are the basic details that have been considered as reference values in this study:

Investment: Rupees 30,000 (750 Euro) per kW capacity
Emission Coefficient: 0.87 kg CO_2/kWh_{el}
Plant load factor : 0.64 (5606 hrs./yr.)
Existing capacity in base year (1999-2000): 55969 MW
Efficiency: 37%
Plant life: 40 years
CV of coal used: 17500 kJ/kg.

Pressurised Fluidised Bed Combustion Based Coal Power Plants

Pressurized fluidized bed combustion (PFBC) systems are basically turbo-charged versions of Atmospheric Fluidised Bed Combustion (AFBC) which was the initial development in this field. PFBC systems can operate in combined cycle configurations, using both gas and steam turbines. The gas turbine cycle generates about 20% of the electrical output and also supplies pressurized air at up to 20 atmospheres to the fluidized bed system. The pressurized air provides for greater combustion efficiency. Limestone sorbent is used to capture sulfur released by the combustion of coal. Jets of air suspend the mixture of sorbent and burning coal during combustion, converting the mixture into a suspension of red-hot particles that flow like a fluid. Elevated pressures and temperatures produce a high-pressure gas stream that drives the gas turbine, and steam generated from the heat in the fluidized bed is sent to a steam turbine, creating a highly efficient combined cycle system. They can even operate at efficiencies of up to 42% and reduce sulphur emissions even more than AFBC units. Research on PFBC systems is still going on. The plants are more costlier but more fuel efficient then the conventional plants as evident from the figures considered in this study as given below:

Investment: Rupees 33,500 (840 Euro) per kW capacity
Emission Coefficient: 0.80 kg CO_2/kWh_{el}
Plant load factor : 0.64 (5606 hrs/yr.)
Existing capacity in base year: 500 MW
Efficiency: 41.5%
Plant life: 40 years
CV of coal used: 17500 kJ/kg.

Integrated Gasification Combined Cycle Coal Power Plant

These plants are advanced versions in the category of coal power plants. Coal gasification is a process that converts solid coal into a synthetic gas composed mainly of carbon monoxide and hydrogen. Coal can be gasified in various ways by properly controlling the temperature, pressure, and mix of coal, oxygen, and steam within the gasifier. Most of the gasification processes use oxygen as the oxidizing medium. IGCC, like PFBC, combines both steam and gas turbines (combined cycle). Depending on the level of integration of the various processes, through IGCC up to 45% efficiency is achievable.

In the initial stages of the process, fuel gas leaving the gasifier is to be cleaned thoroughly of sulfur compounds and particulate. Cleanup occurs after the gas has been cooled, which reduces overall plant efficiency and increases capital costs. Cleaning is also possible under high pressure and temperature (hot-gas cleanup) which increases the plant cost but also increases the efficiency. Besides eliminating sulfur and particulate emissions, IGCC technology also has relatively lower CO_2 emissions. Another advantage of IGCC is that even inferior quality coal can also be used with this technology which is relatively cheaper. IGCC is a developing technology, and information directly relevant to Indian conditions was not readily available. Therefore, information from most appropriate literature [Bansal 2000], [Govil 2000] has been considered unlike field information in the previous two cases.

Investment: Rupees 60,000 (1500 Euro) per kW capacity
Emission Coefficient: 0.73 kg CO_2/kWh_{el}
Plant load factor : 0.64 (5606 hrs/yr.)
Existing capacity in base year: 500 MW
Efficiency: 45%
Plant life: 40 years
CV of coal used: 17500 kJ/kg.

Natural Gas Based Power Plants

Natural gas has many advantages over coal as a fuel for generation of electricity. Natural gas based plants enjoy advantage of much lower air polluting emissions, less construction time, greater efficiencies, as well as better modularity and reliability compared to coal-based technologies. Until now, the main barrier to greater use of these superior technologies in India, has not been the plant cost but actual and the perceived lack of natural gas supply at relatively higher prices than coal, as mentioned in section 5.3.

Natural gas turbines generate electric power by expanding a hot gas through a series of turbine blades connected to an axis that turns a generator. Combustion turbines operating in single cycle have efficiencies up to 42%. Simple cycle combustion turbines have very low capital costs and may have an important role in generating peak load power. However, combined cycle systems have much greater potential to improve the overall performance of gas based power generation.

The combined cycle natural gas turbines based power plants are advanced version of the simple cycles, having potential of offering efficiencies approaching 55%. Installation costs of mid- and large-size CCGT systems are reported to fall continuously due to continuous technological advancements. The most critical components of gas turbines determining overall efficiency and design life are the first-stage turbine blades and combustion chamber walls. Efficiency gets boosted as the combustion temperature increases, but the critical components mentioned above are easily damaged at the current firing temperatures of over 1200ºC.

In, India, Bharat Heavy Electricals Limited (BHEL) is one major manufacturer of indigenous turbines that helps controlling the costs of plants by reducing requirement of imported equipment from developed countries. Although there is often a time lag in utilization of state-of-art technologies but over the years this lag has been reduced to a large extent [Hindu 1999]. Therefore, parameters, related to indigenous gas power plants have been taken in the base case, however, international state-of-art has also been covered through the sensitivity analysis. Main parameters used in this study concerning gas turbines power plants are as given below:

Investment: Rupees 30,000 (750 Euro) per kW capacity
Emission Coefficient: 0.48 kg CO_2/kWh_{el}
Plant load factor: 0.64 (5606 hrs./yr.)
Existing capacity in base year: 7805 MW

Efficiency: 40%
Plant life: 30 years
CV of gas: 41800 kJ/cu. m.

Oil Thermal Power Plants

Oil based thermal power plants are to a large extent similar to simple cycle gas power plants. Except smaller units, in these power plants, oil is atomised in the form of tiny particles for facilitating faster combustion of fuel in the combustion chamber to get more power output. After evaporation of oil droplets through atomisation, a mist like air-fuel mixture is formed that is comparable with mixture of natural gas and air in case of gas power plant. There are few other differences like fuel handling equipment as compared to gas power plants but more or less the plants are similar in cost, plant life etc.. Main parameters considered in this study are as given below:

Investment: Rupees 30,000 (750 Euro) per kW capacity
Emission Coefficient: 0.70 kg CO_2/kWh_{el}
Plant load factor: 0.64 (5606 hrs./yr.)
Existing capacity in base year: 500 MW
Efficiency: 39%
Plant life: 30 years
CV of oil: 44165 kJ/kg

Nuclear Power Plants

The nuclear power sector in India is totally governed by the central government through Nuclear Power Corporation with its helping organizations like Bhabha Atomic Research Center (BARC) for carrying out research and development related activities. India has an ambitious plan for accelerating the use of nuclear technology in forthcoming years. Nuclear power plants could avoid many of the environmental problems associated with combustion of fossil fuels, but high-level waste disposal and the risk of accidents present environmental challenges of a different magnitude that often overshadow their advantages. Due to the typical nature of associated problems, strict control of government on this sector and probably defense related expansion plans, this type of power plants are covered in this study in a special way, not among normal competing technologies. This has been done by assigning fixed capacity bound of the value equal to the capacity addition projected by the government sources [NPC 1999], in future time periods of the model. The advantage of adopting this approach has been inclusion of nuclear power technology in this study with realistic terms and conditions. The model, thus is not free to comment on the desired nuclear power capacity.

The Indian government has approved a three-stage plan for expansion of nuclear power sector. In the Stage-1, 10000MW capacity through uranium fuelled PHWR based plants is envisaged. In Stage-2, installation of fast breeder reactors with plutonium as fuel and thorium as blanket for breeding U_{233} and in Stage-3, installation of breeder reactors using U_{233} as fuel and thorium as blanket is planned [NPC 1999]. In a discussion termed 'vision 2020' installation of 20000 MW power generation capacity has been planned.

As the construction time for nuclear power plants is 8-10 years, plants already sanctioned or awaiting sanction only are expected to be available after 8-10 years i.e. by the year 2010. Such plants will provide additional capacity of about 8000 MW. Similarly, plants that are already under construction will only be available till the year 2005, these amount to availability of about 2500 MW additional capacity in the year 2005 [NPC 1999]. Expected available capacity in year 2015 has been found through interpolation using expected new capacities in years 2005, 2010 and 2020 for use in the MARKAL analysis. Following parameters related to nuclear power plants, have been also been used in this study:

Investment: Rupees 90,000 (2250 Euro) per kW capacity   Efficiency: 33%
Plant load factor: 0.75 (6570hrs/yr.)   Plant life: 40 years
Existing capacity in base year: 2200 MW

5.4.2 Renewable Energy Based Technologies

Large Hydro Power Plants

Hydro power is the second most widely accepted technology for power generation in India, after coal power plants. The much quoted estimated potential of slightly more than 84,000 MW capacity is for sites offering minimum of 60% PLF due to availability of water. This potential is considered as economic potential for hydro power in India. Its value increases to 135,000 MW if some additional sites, offering more than 40% PLF are also considered [Naidu 1996]. Therefore, a sensitivity analysis has been carried out for this additional hydro potential in the chapter 8. As the reference value however, the established figure of economic potential (rounded-off to 85 GW) only is used in the MARKAL analysis as upper bound for this technology.

Besides the availability of water, environmental impacts of hydro power plants also need to be examined thoroughly while considering construction of large hydropower plants. Some of these considerations are the mass resettlement of families, the threat of catastrophic structural failure, the loss of tourism and recreational potential, the impact of silt buildup, the loss of agricultural land, the runoff of pollution into the reservoir, the effects on local flora and fauna, and decommissioning the dams. Other positive benefits related to hydropower plant construction, including flood control and improved navigation, also need to be considered. Construction of hydro power plant is relatively more capital intensive and time consuming. Coverage of rehabilitation and restoration costs (that are very much site specific) further increase the overall project costs. For the basic case of this study, average Rehabilitation and Restoration (R&R) costs have been considered as available from the sources of the National Hydro Power Corporation [NHPC 2001] and the Power Finance Corporation of India [Govil 2000]. Parameters considered in this study are as given below:

Investment: Rupees 60,000 (1500 Euro) per kW   Plant life: 60 years
Plant load factor: 0.60 (4380 hrs./yr.)   Existing capacity in base year: 21891MW

Small Hydro Power Plants

Unlike large hydro, small hydropower plants usually rely on run-of-the-river configuration and do not require large reservoirs. Therefore, while this eliminates many of the environmental impacts of larger dams like deforestation, submergence and rehabilitation, it also reduces project gestation period and offers higher operational flexibility. In India, capital costs per unit capacity for small hydro power plants are higher than the larger units due to economies of scale and also due to lack of proper thrust to related research. However, the costs are likely to come down in future [Naidu 2000].

Definition of small hydro power is different in different parts of the world. In India, plants of station capacity less than 15 MW are put in this category. In UK and Germany this limit is 5 MW, in Australia 20 MW, in China 25 MW and in Philippines and New Zealand it is 50 MW [Naidu 2000]. World Bank, on the other hand, accepts the classification based on financial outlay of the projects. Projects with cost less then or equal to Rs.1000 million (in 1997-98) were put in this category. This financial ceiling is subject to revision due to factors like inflation. A contradiction has been observed between this and previous value of limits. The world bank limit is corresponding to a maximum capacity of 25 MW (approximately) as per the contemporary costs [Naidu 2000]. With this new limit of 25 MW, the potential of small hydro also gets increased from 10,000 MW to close to 20,000 MW. As world bank is one of the major funding agencies in Indian power sector, the later value is considered in this study as upper bound against much quoted potential of 10,000 MW. Indian Renewable Energy Development Agency (IREDA), is a national level funding agency and nodal agency for world bank as well for funding renewable energy projects in India. This agency also offers special loans with the limit of 25 MW capacity under the head small hydro [Naidu 2000]. Key parameters, considered in the base case of this study are as given below:

Investment: Rupees 74,000 (1850 Euro) per kW capacity	Plant life: 60 years
Plant load factor (PLF): 0.60 (4380 hrs./yr.)	Existing capacity in base year: 500 MW

Unlike most of the other technologies, there is much variation in parameters related to small hydro power plants. Due to non-availability of reliable information for this break-up, just one category has been made as also done by CEA in their analysis [CEA 1998]. Therefore, variation in cost has been covered through sensitivity analysis, later in this work.

Solar Photovoltaic (PV) Power Plants

Photovoltaic cells convert solar energy directly into electricity. Once used only in space because of their vary high costs, PV cells are found everywhere today from watches and calculators to irrigation pumps and rooftop power supplies. Benefits of photoelectric power include high reliability, modularity, and low pollution. Multinational petroleum firms such as British Petroleum and Shell are investing heavily in PV production facilities and research as the present costs and efficiencies are not sufficiently attractive to compete with conventional technologies. New thin-film PV cells have lower costs, greater efficiency, and longer life than traditional silicon-based cells, making them priority research topics for scientists all over the world. In the base case of this study, we have taken the specifications and parameters relevant in Indian context as given below:

Investment: Rupees 300,000 (7500 Euro) per kW capacity Plant life: 25 years
Power station utilisation factor: 0.15 (1300 hrs./yr.) Existing capacity in base year: nil

Similar to gas turbines, PV related field in India also has a time lag concerning the level of state-of-art with respect to the developed countries. Therefore, the values taken for building basic Reference Energy System (RES), represent parameters relevant for Indian conditions. Information has been collected from PV system manufacturers and also from one 'Solar Power' project coming up in the state of Rajasthan [REDA 2001].

Wind Power Plants

Wind power is the most widely accepted renewable energy technology on date besides hydro power. One of the large barriers to greater wind based power plants is relatively low and varying capacity utilisation of plants. It is evident from the very fact that sites offering more than 20% utilisation factor even are often considered to be attractive. However, the estimated economic wind energy potential of 20,000 MW in India is corresponding to 40% utilisation factor which is considered to be very good in its category. Wind is not a much dependable source of energy and uncertainties in wind velocities over a time period are to be covered through Weibull's distribution as explained in chapter 3. One way to overcome these limitations is by using storage devices which can continue producing power for the grid even when the wind is not blowing. In many areas, where world class winds are available, there are water shortages preventing its use as a storage medium. Compressed air energy storage or flywheels might help overcome the poor capacity factor of many wind sites in these water-poor regions.]. Use of any energy storage technique tends to increase plant cost, such variation in cost and utilization factor with respect to relatively not so economic sites for wind energy systems has been covered through the sensitivity analysis. In India, due to a long coastal line,however, many sites are found to offer even more than 50% utilization factor and relatively stable wind profile [Mani 1993]. Therefore, many wind energy systems are feeding electricity to the main grid without requiring big energy storage systems. Details have been taken for this study from many working power plants and the basic parameters given below are from a recently commissioned two wind energy power plants at Deogarh and Falaudi in the state Rajasthan [REDA 2001.

Parameters related to wind energy base power plants, used in this study are as given under:
Investment: Rs.40,000 (1000 Euro) per kW capacity Plant life: 20 years
Plant load factor: 0.40 (3500 hrs./yr.) Existing capacity in base year: 1500MW

Overview of Key Figures of Technologies in MARKAL Analysis

A summary of values used in defining the reference energy system of MARKAL has been presented through table 5.4. Additional information has further also been given in table 5.5 later and explained through the text of section 5.5.

Table 5.4: Overview of Key Figures of Selected Technologies

Technology	**Efficiency** (%)	**Emission coefficient** Kg. CO_2/kWh	**Investment cost** Rupees/kW	**O&M cost*** **(fixed)** Rupees/kW/yr.	**O&M cost*** **(variable)** Rupees/kWh
Conventional coal power plants	37%	0.87	30,000	800	0.35
PFBC based coal power plants	41.5%	0.80	33,500	920	0.40
IGCC based coal power plants	45%	0.73	60,000	1200	0.55
Large hydro power plants	--	--	60,000	800	0.35
Small hydro power plants	--	--	74,000	500	0.25
Natural gas based power plants	40%	0.48	30,000	800	0.35
Oil based power plants	39%	0.70	30,000	800	0.35
Nuclear power plants	33%	--	90,000	1600	0.60
Photovoltaic power plants	--	--	300,000	400	0.20
Wind energy systems	--	--	40,000	320	0.15

* *Figures do not include administrative and other overhead costs*

Comments on technologies not covered in this study

Few technologies like fuel cells, solar thermal power and bio-mass conversion, have not been covered in this study mainly due to the following reasons:

1. Technical know-how has not yet matured and spread over all parts of the world. Full scale commercial activities will take some time to pick-up. At the initial stages such technologies are expensive and frequently taking place R&D breakthrough suggest waiting for some more time. This is important for countries like India, where there is always a financial crunch restricting the freedom of experimenting with very new technologies.
2. Their use as centralised power generation facility is not as attractive as decentralised use, which is out of the scope of this study.
3. In case of technologies like solar thermal power, better uses like water heating, crop drying etc. are there that are well accepted and proven rather than electricity generation. Harnessing solar energy as low grade energy (heat), converting it in high grade energy (electricity), and again possibly using

it in the form of low grade energy (e.g. for water or space heating, cooking etc.) is even thermodynamically not very attractive against the photovoltaic systems. Therefore, solar thermal systems have also not been covered in the scope of this work. Though, few power plants are operational in some of the countries, but most of them are more in the form of pilot projects than purely commercial ventures.

4. Besides above discussed technologies, know-how of other technologies like geothermal, tidal, ocean thermal gradient, wave energy exist and India has considerable potential for most of these technologies. Limited supplies of technology or other technical and financial barriers inhibit their wide-scale application in India, and so these are also kept beyond the scope of this study.

5.5 Reference Energy System of Indian Power Sector

The Reference Energy System (RES) 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 energy demands. Most convenient way of expressing the RES is through its pictorial format that is a networked diagram indicating energy flows and the associated process parameters (e.g. efficiencies) of technologies employed in various stages of the energy system. In MARKAL, building the reference energy system therefore, was the first step towards building model of the Indian power sector. Besides the technical and financial parameters related to different stages of the RES, some macroeconomic parameters are also required by MARKAL. These are as explained below:

5.5.1 Generic Details

1. Base year: Year 1999-2000 has been taken as the base year for this study. This has been indicated as year 2000 in this study as MARKAL accepts just one year as parameter.
2. Duration of study: 25-year duration or time span has been covered in this study. In most of the similar studies, similar time span has been covered. Although some short-term studies taking 10 year time span have also been conducted, but as MARKAL is considered to be more useful for long term analyses, 25 year horizon has not been shortened. Since the degree of uncertainty related to economical and technology related parameters increases with time span of future, option of higher time-span values (more than 25 year) have also not been considered.
3. Length of periods: Five year length of each period has been kept in this study. The entire span of 25 years has been divided in five periods of five years each. The value of five years has been chosen due to the influence of governmental policies that are framed in the form of 'Five Year Plans'.
4. Discount rate: Financial discounting at a rate of 10% per year has been kept in this work. This rate has been used by the model to find the 'net present value' of any price or cost in the base year from the price/cost in n^{th} year in future. Prevailing rates of interest payable on 'fixed deposits of money' in Nationalised Banks are close to 10% and this has been the dominating reason for keeping the discount rate of 10%.

5. Purpose of all the plants covered in this study is to feed the electricity grid. In industrial countries however, renewable energy systems like wind power plants are mainly used to reduce the load duration of conventional plants. In case of India, there always exists a possibility of consumption of additional power as the economic growth is not stabilised and the growth of many sectors is restricted due to shortage of power.
6. No heating load that is met through the heat energy produced in energy conversion processes is considered in the RES. As in India, requirement for space heating is only for about 2 months in a year, use of electricity is preferred and laying of piping etc. for heat transfer is avoided unlike Western and European countries.
7. Transmission and distribution losses amounting 20% of the generated electricity are considered as national average. Although, in some parts of the country these are much higher, this analysis is kept independent of the regional variations.
8. Except in the scenario of learning technologies (explained in next chapter), technology costs are considered to increase at the rate equal to the national inflation rate. Cost reduction or increase at a different rate in case of some technologies, is covered through the sensitivity analysis.
9. Costs of various power plants are taken from Indian sources only rather than converting the costs in other countries into Indian currency. This has been done because costs in different countries may have some hidden extra cost that may not be relevant here. For example variation in environmental regulations and quality of fuel necessitates different type emission control equipment in different countries. A mismatch has been observed in the costs of power plants world-wide

The above points have been used for supplying input parameters for MARKAL analysis. Few global parameters are also needed for the modelling that have been summarised in table 5.5 given below:

Table 5.5: Global Parameters of the Study

Span of study	Year 1999-2000 to 2024-2025 (represented as 2000-2025)
Base year	Year 1999-2000 (represented as 2000)
No. of periods	5
Span of each period	5 years
Discount rate (of currency)	10%

The simplified form of Reference Energy System is shown in figure 5.9. As the objective of this study is focused on power generation capacity and its utilisation; stages like, end use technology (considering details about lighting load, cooling load etc.) have been merged into their respective sector-wise power demands. As these demand figures do not represent end-use demand, but address gross sector demand, detailing related to the end-application stage were also not required for this modelling exercise. Similarly, the cost of fuel extraction other similar figures have not been specified separately, as final figures of cost of fuel for the power plants, which includes costs of all previous stages, have been considered directly.

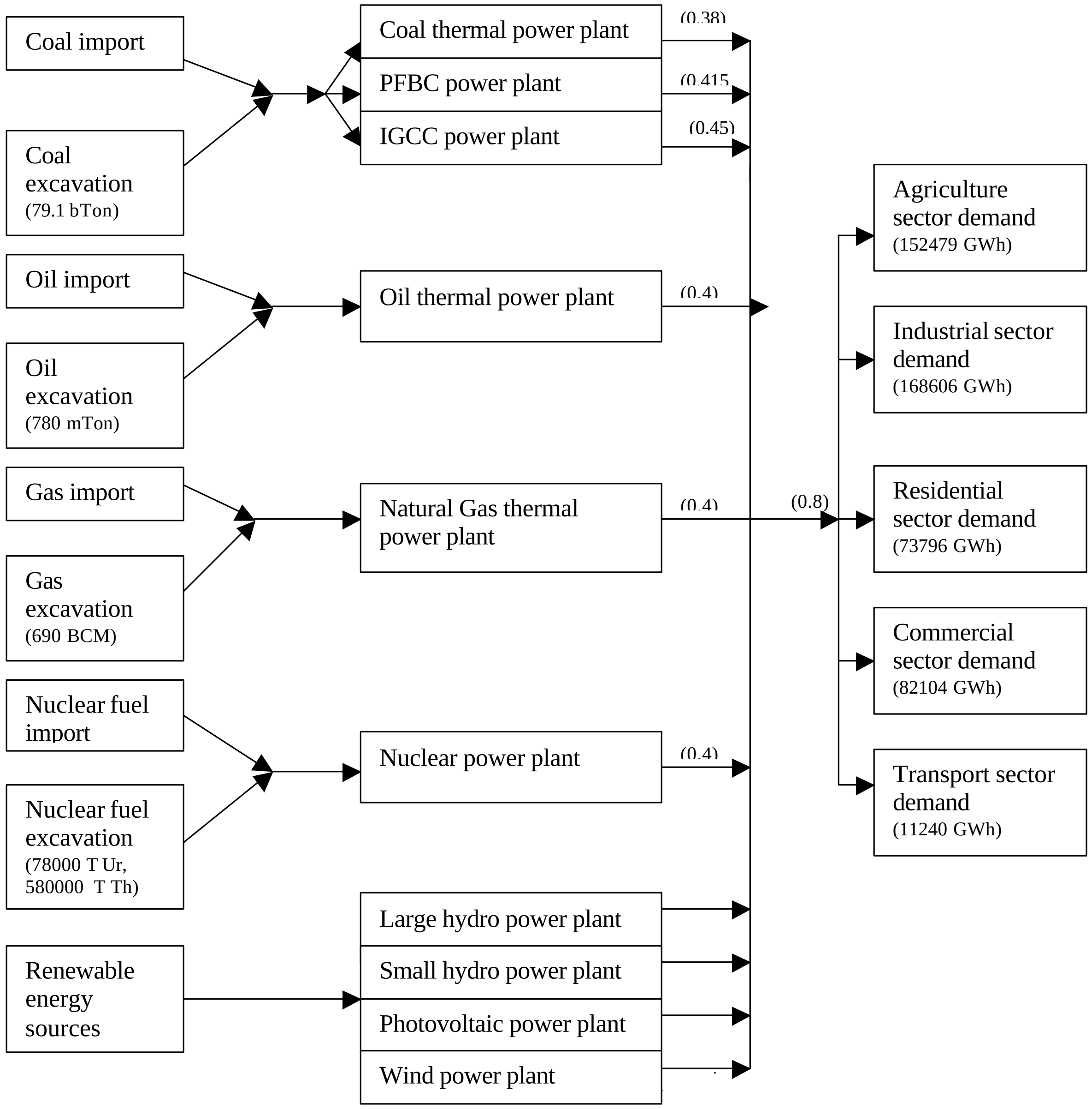


Figure 5.9: Simplified Reference Energy System of Indian Power Sector
(Values shown indicate proven reserves, conversion & transmission efficiencies and demand)
bTon= Billion tons, mTon= million tons, T= ton, BCM = billion cubic meters)

5.5.2 Assumptions and Boundaries of the Study

1. Centralised utilities have only been covered. Non-utilities are out of the scope of this work.
2. Seasonal and daily fluctuations in load is not considered.
3. For addition of new capacity, state-of-art plant will be preferred.

4. Old power plants existing and working at the beginning of the base year will continue to work throughout the period of this study. Taking this assumption is necessary, as in India even very old plants are kept in working condition with necessary maintenance and minor retrofitting. The Power Reforms Committee has also suggested the a similar line of action for future to improve performance of old plants that are close to the end of their theoretical life.
5. Due to opening-up of private sector in power generation sector, there is no constraint regarding availability of money for investment in capacity building.
6. All prices have been indicated in Indian currency i.e. Rupee. This has been done to keep the results independent from the devaluation of Indian Rupee against other international currencies like Euro and Dollar.
7. Prevailing inflation rate in India, has been used to convert price of any commodity or technology in any future year from the price of base year. It is assumed that the same rate will prevail over the entire period of this study.
8. The discount rate used as a global factor, will continue throughout the span of this study.
9. The current growth rate of GDP (gross domestic product) will not deviate from the trend in the last decade. There are some temporary rise and falls in the trend plot due to some extremely favourable or unfavourable year for economy. However, overall growth of GDP has shown a consistency and it is likely to keep the same trend in future. This assumption though was not directly important but governs the trend of increase in energy demand.
10. In general, it has been assumed that sufficient infrastructure support will be present regarding manufacturing, transportation, refining etc., except in the scenarios in which effect of limited infrastructure support is analysed through bound growth (explained in next chapter).
11. Choice among indigenous or imported equipment for power plants is not covered. Different sources may differ the cost involved and also the efficiencies, but including this variation would have complicated the RES without contributing towards the quality of results. Ideally speaking, if authentic data are available, each alternative within one conversion technology, vis-à-vis manufacturer or specification should be treated as one technology for getting specific recommendations from the model.
12. Efficiencies and specific emission values are values corresponding to full load and steady operation of plants. As the plants have been considered to work as base load plants, they are likely to operate under almost steady load close to full load.

Chapter-6

DEVELOPMENT OF DIFFERENT SCENARIOS AND DYNAMIC ENERGY ANALYSIS WITH MARKAL

Scientists and 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 landmarks or events that decide path of growth for future techno-economic scene. However, major possibilities are usually known and should be incorporated in any futuristic planning. Therefore, scope of this work has also been extended to cover major possibilities in the form of various scenarios as shown in figure 6.1.

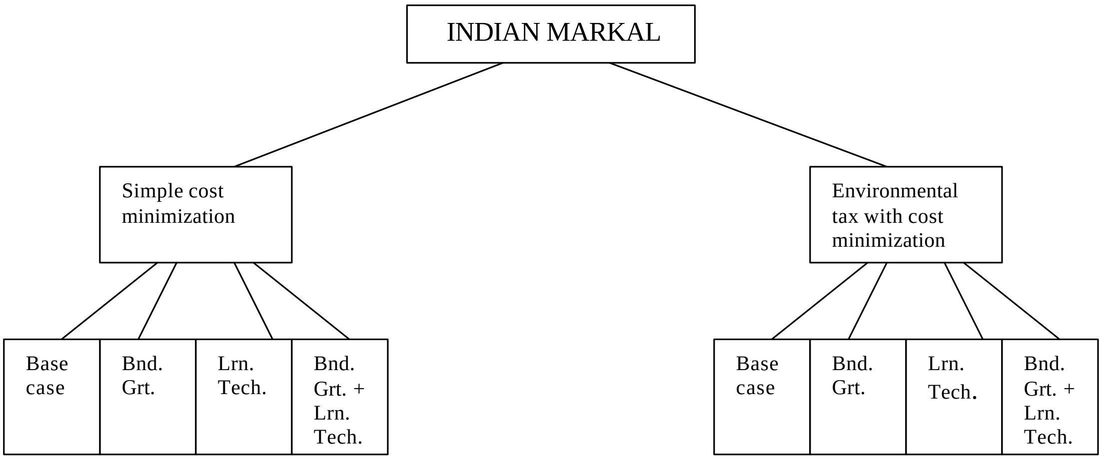


Figure 6.1: Structure of considered scenarios
(Bnd. Grt.: Bound growth, Lrn. Tech.: Learning technologies, Bnd. Grt. + Lrn. Tech.: Bound growth with learning technologies)

Structure of this study has the following two main parts that are explained with details in the next section:

Part 1: Simple cost minimisation: In this part, covers usual commercial aspects related to various technologies like investment cost, O&M cost, fuel cost operating under the defined set of constraints.
Part 2: Cost minimisation with environmental taxes: Introduction of environmental taxes has been considered along with other costs as mentioned in Part-1. Effect of different rates of environmental taxes has been observed.

Each of the above parts have multiple scenarios. These scenarios are:
Scenario 1- Base case
Scenario 2- Bound on growth
Scenario 3- Learning technologies
Scenario 4- Bound on growth and learning technologies

6.1 Major Parts of study with MARKAL

The analysis of Indian power sector with MARKAL has been divided into two main parts. These have been separated as besides cost minimisation the second part has another secondary objective of reduction of greenhouse gas emissions, associated with it. Description of these parts or sections of this study have been given here below.

6.1.1 Part 1: Simple cost minimisation

The first part represents classical MARKAL analysis in which sole objective is minimisation of annualised total discounted cost. Specification of the reference energy system for this part also forms the basic RES for the second part. As shown in figure 6.1 and described later in section 6.2, all the four scenarios have made four sub-sections of part-1. In this part covers the 'Business as usual' practice in which no artificial measures are taken to curb the environmental degradation. Technologies compete in the defined Reference Energy System to meet the power demand only on the basis of their costs and availability. This part is important as introduction of any new policy tool like emission taxes can be compared with the results of this part for judging its effectiveness. Sub-sections of this part called as scenarios depict four different forms and combinations of economic and technological conditions in the country.

6.1.2 Part 2: Emission Reduction

Energy sector is responsible for more than two third of the total greenhouse emissions world wide and also in India due to its large dependence on fossil fuels. Burning of fossil fuels is always associated with environmental problems due to emissions though efforts have been made to minimise emissions. These emissions have given rise to many problems out of which 'global warming' is considered as one of most important ones. Since 1990, several major scientific studies have been conduced by the Intergovernmental Panel on Climate Change (IPCC), which jointly established a 'Discernible Human Influence on Global Climate'. In 1992, a supplementary report of the 'Working Group-1' of the IPCC reconfirmed the initial assessments and projected the range of probable change in global mean temperature. Because of these projections, in 1992, at the Rio Earth Summit, 167 countries identified urgent need and agreed to arrest these environmental problems. In December 1997, these nations began to address the problem of global warming by forging the Kyoto Protocol, which was a follow-on to the original climate change treaty. Specifically, the protocol aims to cut the combined emission of greenhouse gas emissions from the developed countries by about 5% from their 1990 levels by 2008-2012 time frame. It specifies the amount each industrialised country must contribute towards meeting reduction goal. The treaty is ambiguous regarding the role and extent to which the developing countries like India should participate towards reducing the greenhouse gases. However, the Kyoto Protocol does not impose any binding limits on developing countries [WRI 1999].

Before the Kyoto Protocol, under the United Nations Framework Convention on Climate Change (FCCC), the Berlin Mandate was established for strengthening the commitment of developed countries for limiting greenhouse gases. ETSAP (Energy Technology Systems Analysis Programme, Netherlands; presented a multinational analysis of Quantified Emission Limitation and Reduction Objectives (QERLOs) using MARKAL [ETSAP 1999] for eleven countries including India. In this report possible greenhouse gas reduction in these 11 countries has been analysed by introduction of carbon tax at different rates. Loulou R. et. al. [Loulou 1997a] have found the stabilisation rates for carbon taxes in Indian context. In our work, the values obtained by Loulou et. al. have been considered to find reference values for the starting year i.e. 2000. Four different cases with 25%, 50%, 100% and 200% of this reference tax have been considered for making cases of emission taxes for greenhouse gases (represented in terms of equivalent carbon dioxide in this work). For the period after the year 2000 i.e. the base year, an increase at the rate of the inflation rate (6.5% per year) has also been considered in the tax rates. Summary of considered tax rates has been given in table 6.1 and figure 6.2. Each of the four scenarios namely, the base case scenario, bound growth scenario, learning technology scenario and bound growth with learning technology scenario, have been modelled for all of these four emission tax rates making sixteen different combinations of tax, economic and technological status.

It would be worth mentioning here that the possibility of imposing emission taxes depends upon the government's commitment for reducing greenhouse gas emissions, but nevertheless, if the emissions continue to rise with the present trend, there exists a strong possibility of bringing in emission taxes similar to several other legislative measures taken by the government from time to time.

The tax trajectories shown in figure 6.2 are different from the tax trajectories that are often considered for developed countries in some other studies [Gielen 1998]. Reason for this difference is that no deadlines have been set by Kyoto Protocol for reduction in emission level for the developing countries unlike targets assigned to developed countries. Such a grace period for reduction in greenhouse gas emission has been granted, as developing countries require some additional time to develop their infrastructure for their growth. A relatively sharper introduction and increase in tax, as found necessary in case of developing countries, may hamper the growth of these countries.

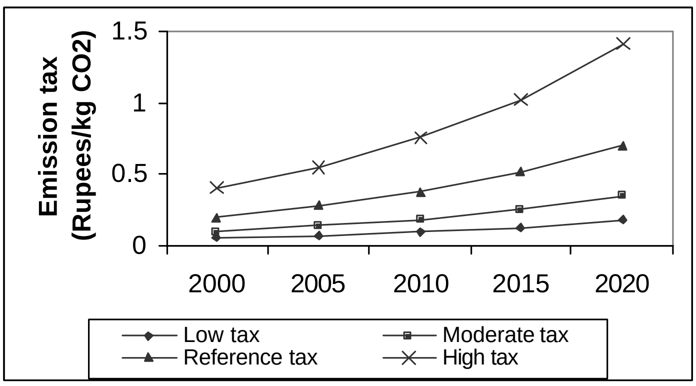


Figure 6.2: Considered trajectories of emission taxes

Table 6.1: Considered emission tax trajectories (Paise/kg CO_2)

	2000	2005	2010	2015	2020
Low tax	5	6.85	9.38	12.86	17.62
Moderate tax	10	13.70	18.77	25.72	35.24
Reference tax*	20	27.40	37.54	51.44	70.47
High tax	40	54.80	75.08	102.88	140.95

**Values rounded-off, converted from Paise/kg Carbon, 1 Paise = 100th part of Rupee, 1 Euro = 40 Rupees in yr. 2000*

6.2 Description of considered scenarios

6.2.1 Base Case Scenario

The base case has been developed in the form of unconstrained development of power generation capacity, except for presence of upper limits for renewable energy technologies as per their respective potentials in the country. No limit on the fuel supply has been kept assuming that during the period of this study, fuel can be imported from international markets if not available indigenously. In a similar study conducted by CEA, Fuel Map of India [CEA 1998], no constraint for fuel availability was kept. In this study, the number of technologies considered was less and no renewable energy technology was studied. In the base case of our study, investment cost, O&M cost have been considered to increase at the rate equal to national average inflation rate as explained in chapter 5. Except for thermal power plants, parameters like plant availability, plant utilisation, conversion efficiencies, have also been kept constant. As per the estimates of Tata Energy Research Institute, India [TEDDY 2000], national average plant load factor of thermal plants is increasing at the rate of 0.4% per year. This increase is likely to continue for next two decades due to the ongoing reforms in Indian power sector and hence has been adopted in our study. As explained in chapter-5, in case of nuclear technology an exception has been made by keeping pre-allocated capacity by supplying fixed bound of capacity equal to the nuclear power capacity expansion plans of the government. However, no compulsion has been kept for nuclear plant utilisation by giving no bound for nuclear capacity utilisation.

6.2.2 Bound Growth Scenario

In a developing country like India, besides availability of fuel reserves, some more aspects may also put constraints on development of technologies in the power sector as possible in the results of the base case scenario. Some of such factors putting restriction on free growth are as listed below:

Growth of mining/extraction facilities
Growth of refining facilities
Limit on fuel imports
Insufficient transportation facilities
Limited production of power plant equipment
Limited money available for investment
Governmental preferences for development of certain sector or region

Due to the limitation of non-availability of reliable data individually concerned with the above mentioned constraints, separate analysis of effect of each one of these bottlenecks was not possible in this work. However, their combined effect has been incorporated by imposing 'aggregate bound on growth of capacity expansion' for each technology.

To arrive at the value of maximum permissible growth of each technology, growth plans of steering bodies of individual sub-sectors in the Indian power sector have been studied. It has been assumed that the growth targeted by these organisations has been fixed considering all above factors and bottlenecks, and growth beyond these targets is not feasible. Summary of the same has been presented below:

In the Eighth Five-Year Plan (1992-1997) prepared by the Planning Commission of India, a total capacity expansion of 30,538 MW was envisaged, out of which 9,282 MW was hydro power, 15,280 MW steam power, 4,876 MW gas power and 1,100 MW nuclear power. In the Ninth Five-Year Plan (1997-2002), a total capacity addition target of 40245 MW has been fixed. Out of which 9819 MW is hydro 23,545 MW is for Coal and Gas based power, and 6,000 MW is the target for liquid fuel based power generation capacity. Besides, is has been planned to develop renewable energy based capacity to an aggregate capacity of 3,000 MW by the year 2002. It has been admitted by the government sources that renewable energy based capacity should reach a level of 15,000 MW by the year 2010 and it is going to be a difficult task as per the present conditions. For the Tenth Five-Year Plan (2002-2007), the National Hydro Power Corporation plans to add a capacity of 12,152 MW [MoP 1999].

Based on the above figures, bounds for each technology for the first period i.e. 2000-2005 have been extrapolated as shown in table 6.2. For the next four periods, an increase in these targets has been anticipated due to growth of economy. Various activities that support or become bottleneck for expansion of power sector have a strong correlation with the GDP growth rate and industrial growth rate. The GDP growth rate touched a high of 7.5% in 1996-97 while industrial growth rate was highest in 1999-2000 at a level of 8.1%. Agriculture sector that is considered to be the backbone of Indian economy, observed highest growth rate of 9.5% in 1996-97. Coal production in India has shown an increase of about 6.5% per year and the planning commission of India has planned to increase it to 10%. Similarly, oil-refining facilities have shown an increase at a rate slightly lower than 10% per year [TEDDY 2000] during past five years. The constraints mentioned above for the expansion of each technology are directly or indirectly connected with the growth of economy and growth of above industrial activities. Therefore, the highest growth rate observed in these influencing sectors has been taken as basis for finding increase in the maximum possible growth of each technology. This means, the upper bound on growth of each technology has been considered to increase at a rate of 10% per annum for all subsequent periods over the bound for the first period. Hence, the values of bounds on growth of each technology are different from other periods. This approach has been found to be in agreement with the growth figures projected by concerned organisations and the Planning Commission of India [PCI 2000].

Summary of the considered bounds on growth for various technologies in different time-periods is given below in table 6.2:

Table 6.2: Growth constraints (Maximum capacity addition in GW) of various technologies

Technology	2000-2005	2005-2010	2010-2015	2015-2020	2020-2025
Coal Thermal	20.000	32.210	51.874	83.544	134.550
Large Hydro	10.000	16.105	25.937	41.772	67.275
Gas Thermal	5.000	8.052	12.968	20.886	33.637
Oil Thermal	6.000	9.663	15.562	25.063	40.365
Small hydro	5.000	8.052	12.968	20.886	33.637
Wind	5.000	8.052	12.968	20.886	33.637
SPV	5.000	8.052	12.968	20.886	33.637

Bounds from Dynamic Energy Analysis

The new approach developed and discussed in chapter 3, also imposes bound on growth of technologies due to their cumulative energy demand. Maximum growth rates for each technology have been found using equation 3.34 and 3.35 using the $CED_{electrical}$ and annual energy as done in section 4.3. Two different cases were discussed while developing the dynamic energy analysis approach. In the first one, all of the energy output from any technology can be used for satisfying its own cumulative energy demand for growth of capacity. In the other one only a fraction of the output can be spared for this purpose. Examination of the maximum growth rates obtained through both the cases suggest that in the first case, growth rates for all the technologies are much higher than the 10% growth rate due to bounds of the economy as discussed earlier. However, in the second case, i.e. the case with 20% reinvestment of energy, growth rates are on both sides of the 10% bound growth rate due to economy as shown in table 6.3.

Table 6.3: Maximum growth rates for self-sustainable programmes

Technology	Max. rate (%) of growth with 20% re-investment
SPV(Mono-crystalline)	6.29
SPV(Poly-crystalline)	8.56
SPV(Amorphous)	11.26
Wind(small)	147.99
Wind(large)	121.89
Hydro(large)	9.35
Hydro(small)	19.26
Coal(advanced)	37.93
Coal(moderate)	41.55
Coal(basic)	43.71
Gas(combined cycle)	58.28
Gas(simple)	112.79

Combined Approach for Bounds

After finding the growth rates from the dynamic energy analysis, each technology has two different values of bound on growth. One is the bound as per table 6.3 (10% increase in growth per year) and the other one is corresponding to the maximum rate of growth obtained through dynamic energy analysis as per table 6.3. The first value represents highest increase in growth due to combination of techno-economic constraints, and the other one (obtained by dynamic energy analysis) is highest possible growth keeping the dynamic energy demand-supply balance for self-development of each technology. Taking the conservative approach for growth (as any of the limit can act as bottleneck for growth) lower value of the two different bounds for each technology has been used for analysis as both the constraints are to be satisfied. In case of large hydro and photovoltaic technologies, the dynamic energy analysis has yielded permissible growth rate lower than 10% per year. Therefore, except for these two technologies, for other technologies, growth bounds as per table 6.2 have been maintained. The modified growth constraints thus obtained have been shown in table 6.4 below:

Table 6.4: Modified Growth Constraints of Technologies (max. capacity addition in GW)

Technology	2000-2005	2005-2010	2010-2015	2015-2020	2020-2025
Coal Thermal	20.000	32.210	51.874	83.544	134.550
Large Hydro	10.000	15.706	24.669	38.746	60.857
Gas Thermal	5.000	8.052	12.968	20.886	33.637
Oil Thermal	6.000	9.663	15.562	25.063	40.365
Small hydro	5.000	8.052	12.968	20.886	33.637
Wind	5.000	8.052	12.968	20.886	33.637
SPV	5.000	7.539	11.367	17.140	25.844

6.2.3 Learning Technologies Scenario

Investigation of history of performance indicators of power plants and pricing of different power generation technologies reveals that there has been a continuous improvement in both of these fields for almost all technologies. Technologies reflect a trend of declining costs and improving efficiencies as a result of increasing adoption into the society and due to 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. A typical learning curve of any power generation technology can be expressed as:

$$SC(C) = SC_0 (C / C_0)^{-b} \qquad (6.1)$$

where: *SC* : *Specific cost as function of C*

C : *Cumulative capacity*

b : *Learning index (constant)*

C_0 : *Initial cumulative capacity (at t=0)*

SC_0 : *Initial specific cost (at t=0)*

At IIASA and Paul Scherrer Institute [Seebregts 1999], [Messner 1997], efforts have been done to obtain learning curves for various technologies and to include learning curves in energy system modelling. According to their findings, in the lifetime of any technology, three distinct stages are distinctly visible. These stages are nascent, developing and saturated stages. In the first stage, technological breakthroughs and successes in R&D sometimes bring unexpected changes in state-of-art and technologies falling in this category are named as ‘Radical’ technologies such as Fuel cells, Solar Photovoltaic Systems. Developing stage of technologies comes after the radical stage when the R&D is relatively grown-up. Technologies falling in this category are called ‘Incremental’ technologies such as Wind Mill, Nuclear Plants, Combined Cycle Power Plants and cost reductions are due to R&D, learning by doing as well as economies of scale. In the last stage or saturated stage, improvements in technologies get slowed down and hence they are called ‘Mature’ technologies such as conventional coal power plants.

Three scenarios have been analysed for modelling the learning of technologies at IIASA. First case is high growth scenario, second one is the middle course or moderate growth scenario and the third one is ecologically driven scenario with strong emphasis on environmental issues. In our study, information about technological learning has been taken from the moderate scenario with sensitivity analysis of other two scenarios. In the referred studies, reduction in investment costs has been projected for the year 2050 on the basis of costs in the year 1990. Following assumptions have been used in this work while analysing the learning technology scenario and for modifying the results for Indian context:

1. Learning trend for power generation technologies, observed internationally, will also be observed in India due to imports of technology and technical know-how.
2. The path of learning in India will be linear from the starting year 2000, up to the year 2050. This assumption was necessary as IIASA has projected investment costs for the year 2050 and costs for the years 2005, 2010, 2015 & 2020 were required for this work.
3. Percentage reduction in the investment costs in India will be same as percentage reduction projected in the study by the referred studies over the period 1990-2050 [Seebregts 1999], [Messner 1997].
4. Technologies that are not covered in the referred studies but identified as radical, incremental and mature technologies will observe learning rate similar to other technologies falling in their respective category. For example, small hydro power plants have not been analysed in the IIASA studies but as this is an incremental technology, learning similar to wind mills has also been assumed for small hydro technology.

Table 6.5 shows details of the learning projected for various technologies using the following equation:

$$C_{2050,India} = C_{2000,India} - \left[\frac{C_{2000,IIASA} - C_{2050,IIASA}}{C_{2000,IIASA}} \right] * C_{2000,India} \qquad (6.2)$$

and

$$C_{n,India} = \left[\frac{C_{2000,India} - C_{2050,India}}{50} \right] * n$$

(6.3)

here: *C_{2000}, C_{2050}, C_n: Investment cost/kW capacity in year 2000, 2050 and n^{th} year*

C_{India}: Investment cost/kW capacity for India

C_{IIASA}: Investment cost/kW capacity considered in IIASA documents

Table 6.5: Effect of Learning on Various Technologies

Technology	Investment cost/kW in 2000 (Rupees in 2000)	Expected % reduction in cost by 2020
Conventional coal	30,000	3.03
PFBC	33,500	5.0*
IGCC	60,000	5.93
Large Hydro	60,000	3.0*
Small Hydro	74,000	10.0*
Gas Power	30,000	10.0*
Oil Power	30,000	3.0*
Nuclear Power	90,000	3.84
Wind Power	40,000	11.9
Photovoltaic	200,000	20.26

** assumptions using [Messner 1997]*

6.2.4 Bound Growth with Learning Technologies Scenario

In addition to considering the 'bound on growth' and 'learning-technologies' scenarios independently, their joint effect on the study has also been observed through this fourth scenario. These are two independent likelihood and various governing factors and developments in one are almost independent from the other. Growth limits as per table 6.4 and effects of technological learning as per table 6.5, have been included in the base case simultaneously for building the combined scenario.

Results of the above mentioned parts and scenarios within each part have been shown in chapter-7. Changes in results seen through sensitivity analysis have been given in chapter-8.

As can be noted in table 6.2 and table 6.4, common growth constraints for all the three coal thermal power plants have been considered as the stated constraints and targets are for all the three technologies considered jointly. Similarly, targets and constraints for setting up renewable energy based power plants are also set commonly by the Ministry for Non-Conventional Energy Sources. However, table 6.3 shows different values of constraints obtained by dynamic energy analysis approach for wind and SPV technologies due to their different CED and annual energy output ratios. Therefore, the reference energy system has been modified by introducing few dummy power plants and by assigning these combined bounds for coal based technologies and for renewable energy technologies to these dummy technologies. The method of introducing dummy technologies has been shown as figure 6.2. In the modified RES, all the power plants that are to be linked together by combined constraint, produce a dummy energy carrier 'Dummy Electricity" that is supplied to the dummy power plant as input. This power plant converts this dummy electricity into electricity as output at 100% efficiency. One set of dummy plant and dummy energy carrier (electricity) are provided for each combination i.e. combined coal power plants and combined renewable energy systems shown as dotted boxes in the figure 6.3 given below:

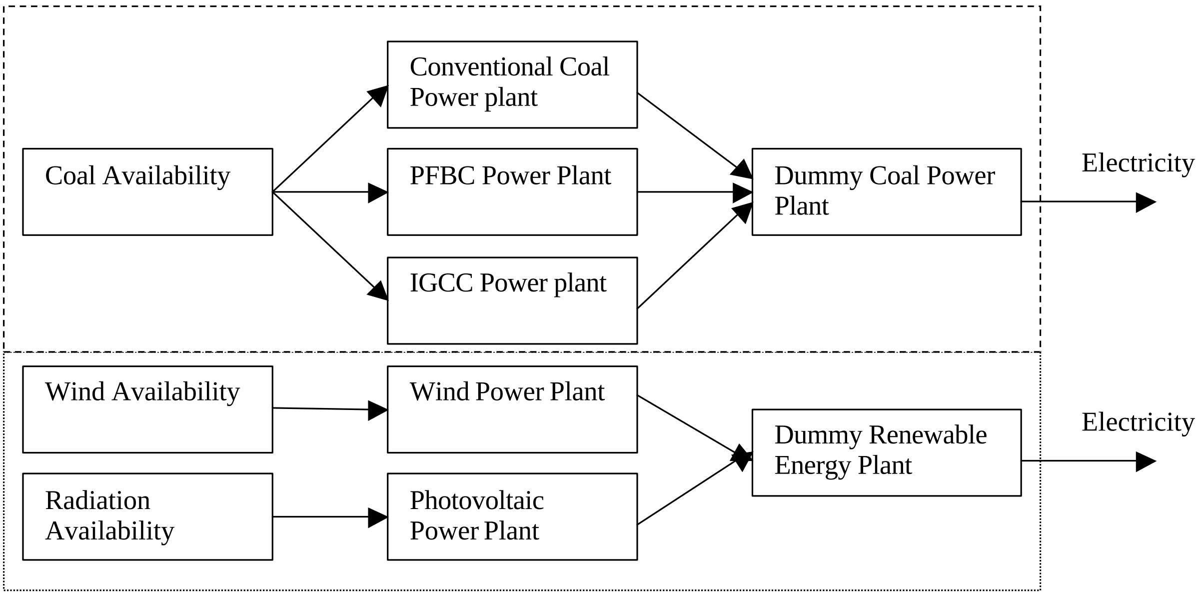


Figure 6.3: Method of modifying Reference Energy System for combined bounds

Results of MARKAL analysis of all the different combinations as discussed in this chapter have been obtained and are presented in the next chapter. In addition, variation in these results due to change in values of key parameters have been discussed in the subsequent chapter of sensitivity analysis.

Chapter-7

RESULTS

The developed model was run for all the cases as described in chapter-6. Analysis of the results shows variation in choices of technology by the model in different periods. They have been arranged in the same order so as to present clearly the effect of various considerations and variations. Graphical representation has been preferred to enhance the readability of results. Exact values can be seen in appendix13 onwards, presenting results in details. In the presentation of results, few technologies i.e IGCC, oil, PV and nuclear power plants have been clubbed together under the head 'others' as in any of the scenarios the model has not varied their capacities. An increase in the total value is however there as the nuclear power plants were allocated fixed capacities as per growth plans of the government.

7.1 Part-1: Simple Cost Minimization

Base case

Results of the simple base case suggest that the model finds hydro power as the most economic option. In the first period, the model prefers small hydro over all technologies and first gives full allocation to it. Remaining allocation is given to large hydro category. In the second period, model has given allocation to wind energy first and remaining allocation again came to large hydro technology. One interesting phenomenon here has been that in the first period large hydro was assessed the second best technology as small hydro was the first choice. In the second period, even if small hydro option is not there as it gets saturated in the first period itself, large hydro again gets remaining allocation after saturation of wind power capacity in the second period. This change comes into picture due to the difference between discount rate and inflation rate. As the inflation rate (6.5% per year) considered in this model is lower than the discount rate (10% per year), ten units of money in terms of cost in base year, after one year become 10.65 units due to inflation. But its value when converted to the equivalent cost of base year gives $10.65/(1+0.1)^1$ giving its value as 9.68 units of money in the base year. This suggests that any cost in future point of time is equivalent to a relatively less cost in the base year. Due to this reason, in the second period, the allocation first goes to wind power and as its maximum capacity gets utilised remaining allocation is given to large hydro. This change makes it necessary to investigate the effect of different inflation and discount rates on the choices that has been done through the sensitivity analysis discussed in the next chapter.

However, results of the current analysis further show that in the third period allocation goes to large hydro as wind energy potential got saturated in the earlier period. The total hydro and wind power potentials get saturated by the fourth period (i.e. years 2015-2020) and therefore, coal is found to be the next most attractive option for capacity expansion. Among the three coal power technologies, conventional coal power is picked up by the model. This is due to the reason that among these three technologies, it has least initial investment and operation and maintenance costs. Low prices of coal do not allow the efficiency related advantage (or fuel saving in other words) of other two coal based technologies to come into picture. Due to relatively high fuel prices, gas and oil based power plants do not get any allocation. The IGCC based coal power technology, as requires too much initial investment, does not come into picture. Growth of various technologies due to allocation given by the model has been shown in figure 7.1.

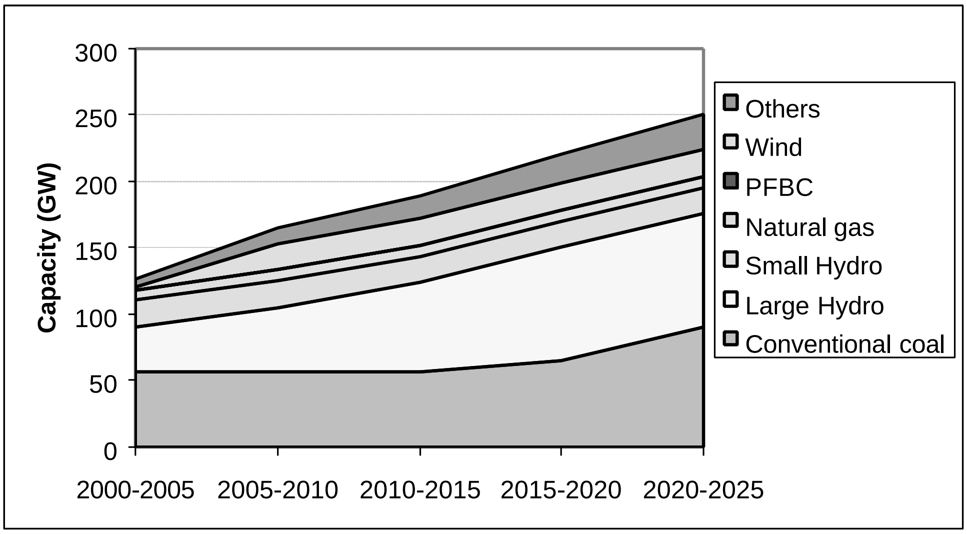


Figure 7.1: Growth of technologies in base case (without taxes)

Effect of Technological Learning

With introduction of learning effect in the investment related to various technologies as describes in chapter 6, the choices get slightly altered. As small hydro and wind power both are relatively fast learning technologies, MARKAL, assesses advantage in waiting for these technologies to learn. Therefore, it picks up large hydro technology first, and after the first period i.e. after five years, when it expects some decrease in investment related to wind power plants due to faster learning rate as compared to small hydro, decision about increase in capacity of wind plants is taken. Wind power capacity gets saturated in the second period itself and by that time, small hydro power investments also come down and hence allocation is given to small hydro power. Large hydro power once again gets some allocation after small hydro and when it is saturated choice goes to coal power plants. There is again found one change due to the effect of learning. As the question about choice of coal power plants comes towards the last periods, the PFBC based technology also learns and becomes more attractive than the conventional coal power plants. Therefore, further allocation is found to be in favor of PFBC technology. Similar to the base case, gas, oil and IGCC based power plants do not appear at all in the results, again.

It would be worth mentioning again the assumption that the technological learning at international level can be adopted in India at any point of time and internationally technologies will continue to learn even without any contribution from India through 'learning-by-doing'. Although, there is always a question mark about the probable learning in case of stopping the installation of plants of certain technologies at all and depending upon the research and development only. Nevertheless, technological learning in developing countries is much dependent upon the developments in the developed countries as their can be import of technical know-how and that is why this assumption has been made for this study.

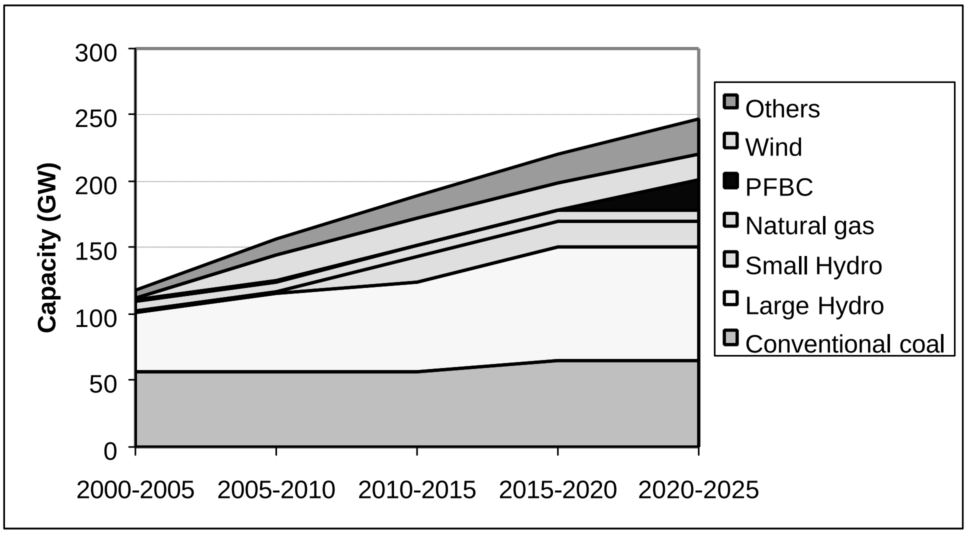


Figure 7.2: Growth of technologies in Learning Technologies Scenario (without taxes)

Effect of Bounds on Growth

The effect of bounds has been observed in the form of restricted allocation for expansion of any one technology. As explained in chapter 6 these bound represent limitations of the economy and infrastructure related limitations for expansion. Therefore, in the base case with bounds, during the first period, small hydro got the allocation up to the maximum limit only, then the allocation was given to large hydro and then wind energy. After reaching limits of these technologies, the model gave preference to conventional coal power plants. In the second period similarly, wind, large hydro, and small hydro technologies grew to their maximum limits. One major result of this restricted approach has been that small hydro technology could not grow up to its maximum potential due to the reason that in future periods it is not among the preferred technologies due to the difference between discount rate and inflation rate as discussed in the base case earlier.

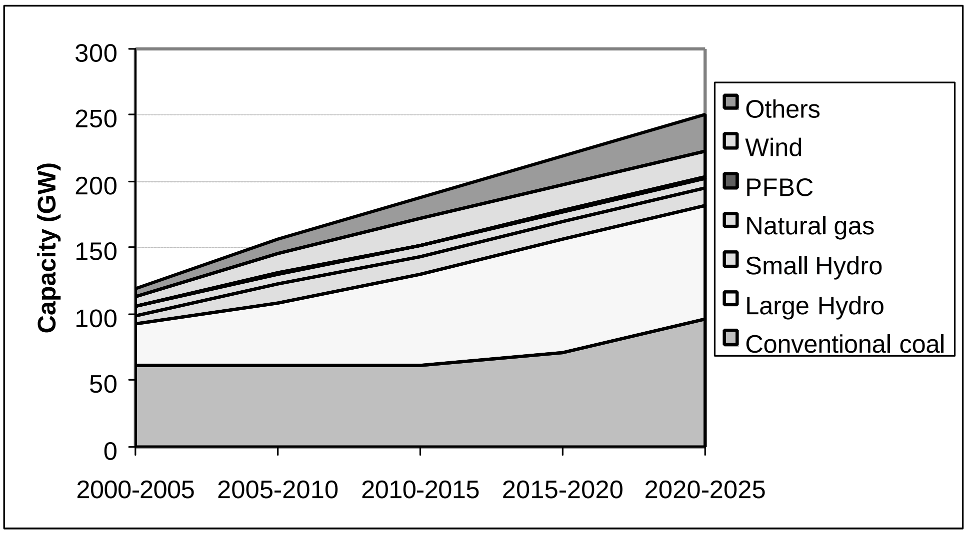


Figure 7.3: Growth of Technologies in Bound Growth Scenario (without taxes)

In case of learning technologies with bound on growth, results were again changed due to the learning phenomenon. Due to relatively higher learning rate , in case of small hydro technology, the effect of difference between discount rate and inflation rate was overcome by reduction in investment. Therefore, in future periods also, it remained to be attractive enough and its entire potential got utilized unlike the previous case. Similar to the simple learning case, in the last period, due to higher learning, PFBC based coal power plants were preferred by the model over conventional coal technology.

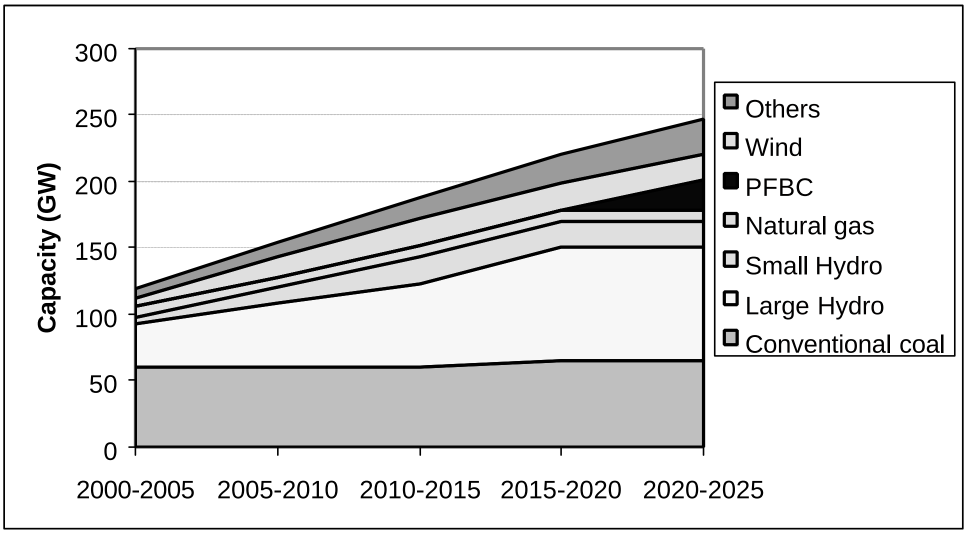


Figure 7.4: Growth of Technologies in Bound Growth + Learning Scenario (without taxes)

7.2 Part-2: Introduction of CO_2 Taxes

As has been explained in section 6.1.2, for different trajectories of CO_2 taxes namely low tax, moderate tax, reference tax and high tax cases have been modelled with the four basic scenarios whose results have been discussed in the previous section.

The Base Case with taxes:

With the introduction of tax at the low rate as mentioned as low tax case, no effect has been observed on the technological choices in the simple base case. In the case of moderate tax with the base case, the choice of PFBC based coal power plants becomes better as compared to conventional coal power plants and hence allocation is given to PFBC coal power plants during the last period where conventional coal power plants had got allocation without taxes and with low taxes. At moderate taxes and high tax rates, the model suggests to have more capacity of large hydro power. A minute inspection of results reveals that the model even prefers to have the fossil based capacity standing unutilised and prefers to invest in additional clean renewable energy based capacity instead of paying for taxes. In the later stages however, due to increase in demand, there is no choice but to use fossil fuel based technologies as renewable energy based technologies cannot cater to the entire demand of future periods. Appendix-17 gives utilisation of plants (in terms of percentage) as suggested by the model in brackets besides the values of recommended capacities. Other technologies like gas, oil, IGCC power plants do not appear in the choices with any of the considered tax rates.

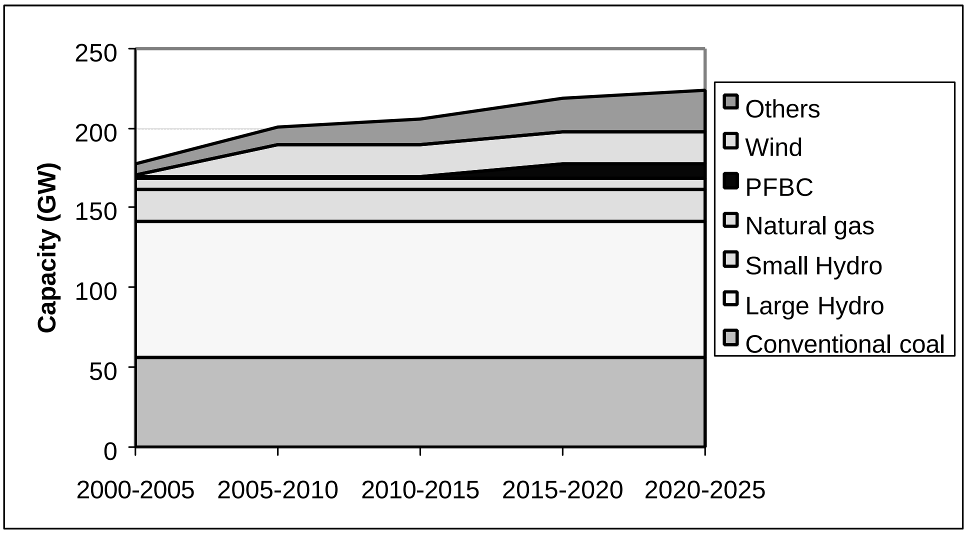


Figure 7.5: Growth of technologies in Base Case (with High Tax)

Learning Technologies with Taxes:

Similar to the base case, in case of learning technologies with low tax rates, no change has been found in choices from the case of learning without taxes. With the moderate tax, the model is not waiting too long for the small hydro technology to learn and is introducing minor allocation to it in the second period instead of paying for taxes. The model once again finds better to invest more for installing more renewable energy based capacity than utilising fossil based technologies. In the later stages similar to the base case, due to increase in demand, there is no choice but to use fossil fuel based technologies. At high tax rates with learning, the models introduces another change by choosing the relatively cleaner and faster learning natural gas based technology and therefore, natural gas based power stations get the allocation instead of the PFBC based coal power plants which otherwise were preferred at lower tax rates.

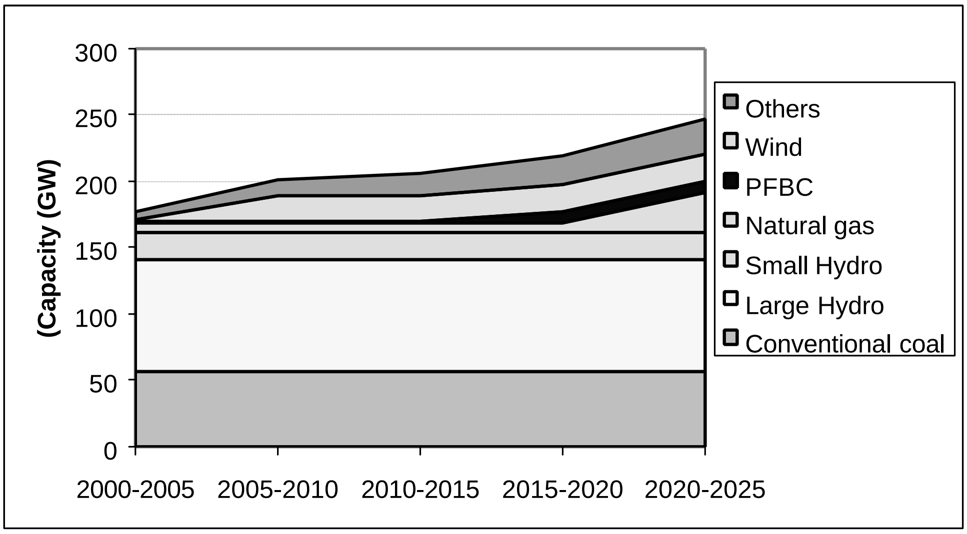


Figure 7.6: Growth of technologies in Learning Technologies Scenario (with High Tax)

Effect of Bound on Growth with Taxes:

With the bounds on growth and taxes, with the low taxes, the model prefers small hydro even in future periods despite the effect of difference between discount rate and inflation rate. As a result small hydro grows to its full potential against the case of no taxes where it was not preferred in future periods as discussed in the earlier section. As observed in previous two cases, with moderate taxes and more, as the taxes increase, the model introduces prefers to introduce more and more clean technologies but in this case such event is restricted by the bounds. As a result there is not much surplus capacity as found in cases without bounds.

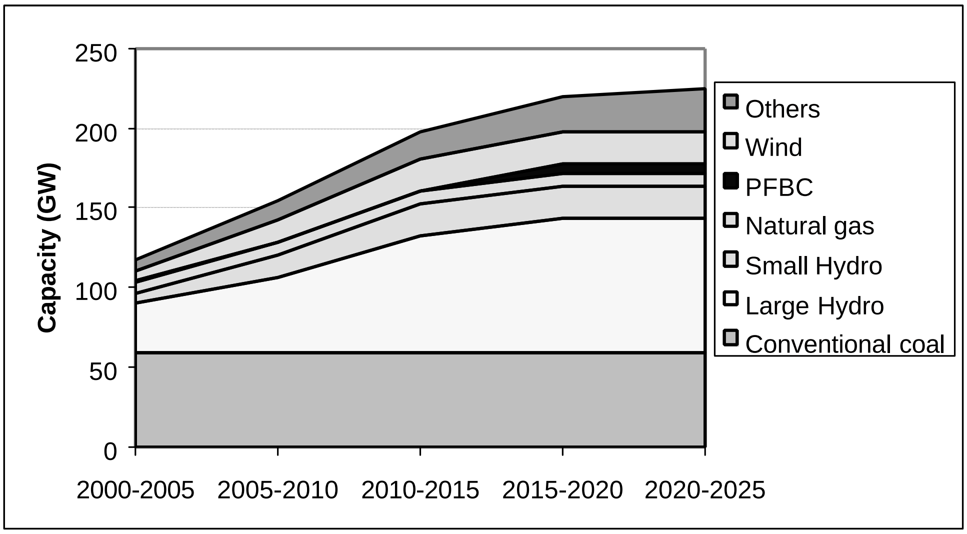


Figure 7.7: Growth of technologies in Bound Growth Scenario (with High Tax)

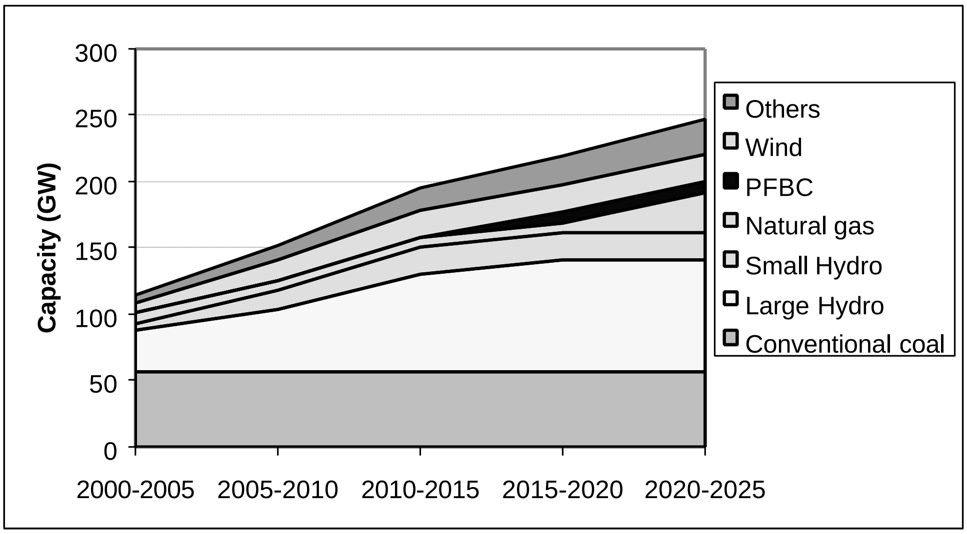
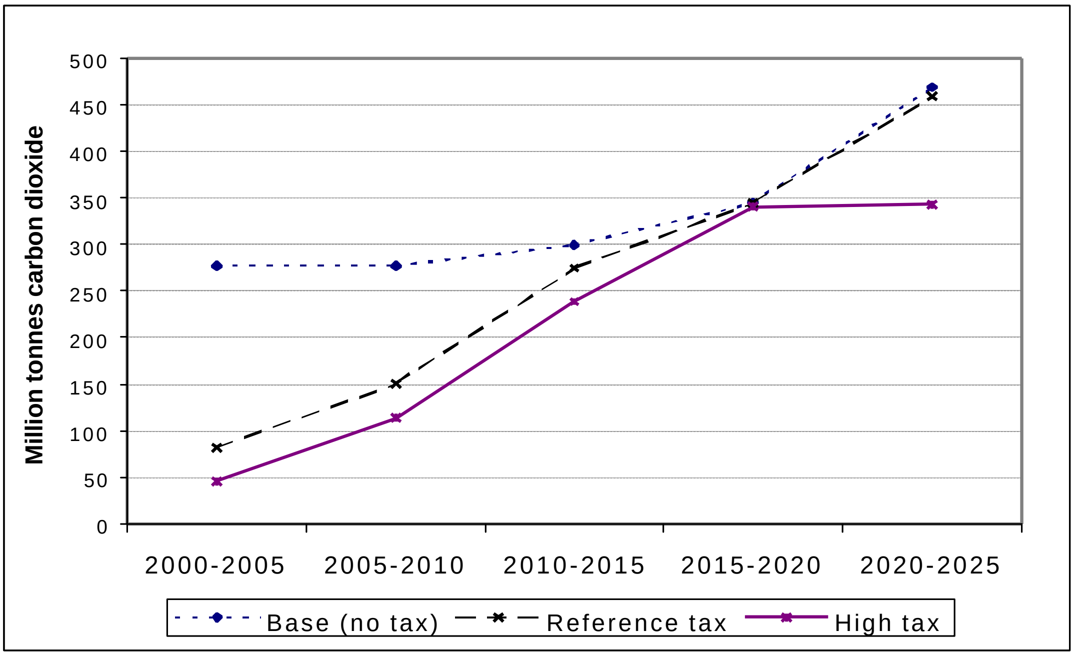


Figure 7.8: Growth of technologies in Bound Growth with Learning Scenario (with High Tax)

7.3: Potential of Reducing CO_2 Emissions

In the base case, with the introduction of CO_2 taxes, up to the moderate rare there is not considerable reduction of emissions as the choices are not altered much. With further increase in rates, it has due to more renewable energy based power generation, emissions come down in the initial period of the study. This advantage however, reduces in future periods due to increase in demand as the freedom of not utilising fossil based capacity reduces. Towards the end, there is about 26% reduction in CO_2 emissions as compared to the case of 'no tax' in the basic scenario as shown in figure 7.9.

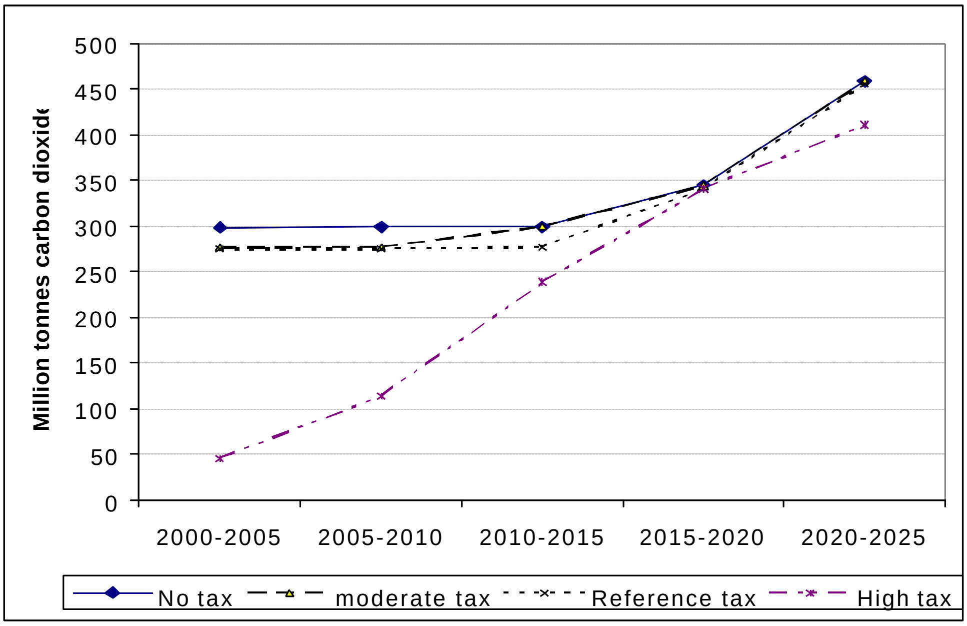


Cases of other tax rates are not shown as they are similar to neighbouring cases (values given in appendix 18)

Figure 7.9: Emission Reduction with taxes in base case

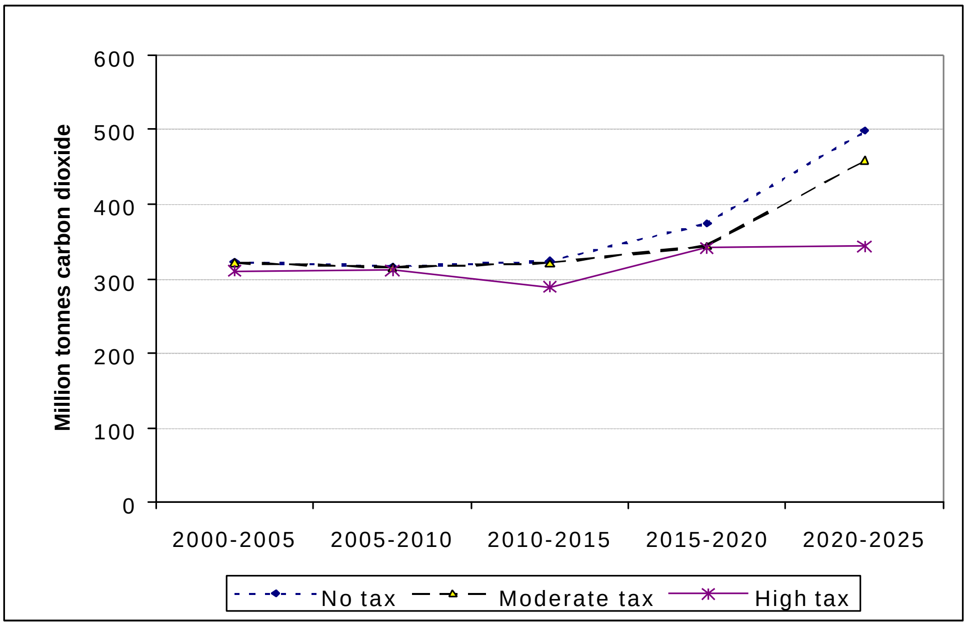
In the learning technology scenario, variation in emissions has been shown in figure 7.10 which suggests that at the beginning, only high tax case is able to reduce emissions much as the model suggests to wait for small hydro to learn for some time. Finally the emissions are about 10.65% less than the 'no tax' case and about 12.3% less than the 'no tax' case of the basic scenario.

In the case of bound growth, in the initial periods reduction in emissions with high taxes gets reduced as the growth of renewable energy based technologies is restricted by the bounds. The resulting emissions in the 'no tax' case of bound growth scenario are higher than the base case due to the same reason. However, emissions in the last period with introduction of taxes are nearly at the same level as in respective cases of the basic scenario. Variation of emissions has been shown in figure 7.11.



Cases of other tax rates are not shown as they are similar to neighbouring cases (values given in appendix 18)

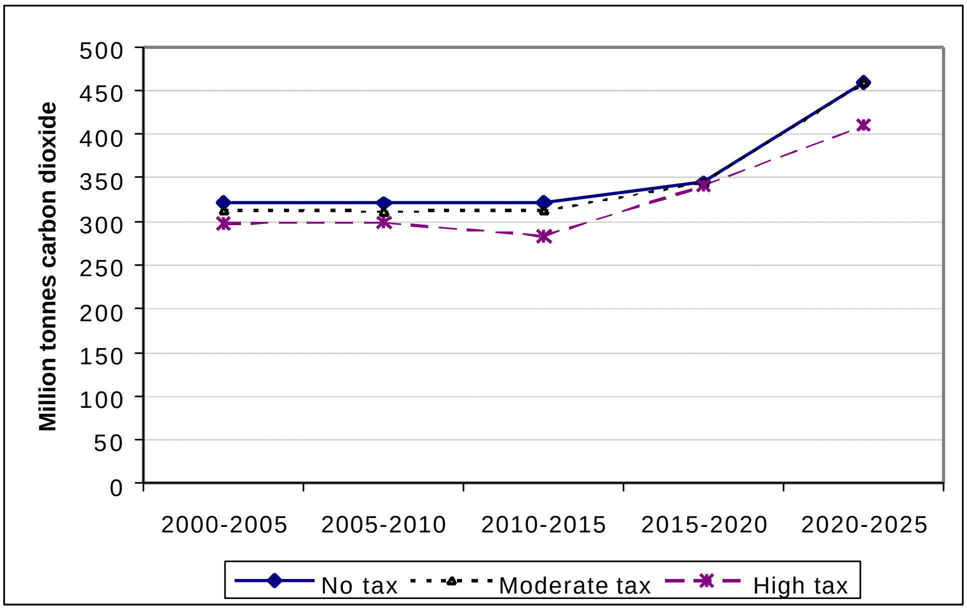
Figure 7.10: Emission Reduction with taxes in Learning Technology Scenario



Cases of other tax rates are not shown as they are similar to neighbouring cases (values given in appendix 18)

Figure 7.11: Emission Reduction with taxes in Bound Growth Scenario

The bound growth with learning technology scenario also suggests that due to restrictions reduction in emissions in the initial period is not much. Variation in emissions related to this scenario with different tax rates has been shown in figure 7.12.



Cases of other tax rates are not shown as they are similar to neighbouring cases (values given in appendix 18)

Figure 7.12: Emission Reduction with taxes in Bound Growth + Learning Scenario

Conclusions based on the results presented above have been drawn and discussed in chapter 9. Before that, to make this analysis comprehensive, the next chapter of sensitivity analysis throws some more light on probable variations in the results discussed above due to major future possibilities that have not been covered through the scenarios and cases discussed in this chapter.

Chapter-8

SENSITIVITY ANALYSIS

This chapter can be treated as an extension of the previous chapter as it presents variation in the results due to change in values of the basic parameters related to various aspects that may affect the discounted cost of the system and affect the technological choices. Affects on the results due to various changes in parameters have been discussed below along with their relevance in the real life situation.

Discount Rate:

This parameter has its importance not only in this work but in every economic activity having dynamic aspects. This factor governs the time dependent value of money which means the worth of money at any point of time can be calculated through this factor. Value of this factor is usually taken equal to the interest rates offered by banks on deposits and for calculating worth of money at any point of time approach of calculating compound interest can be used. For the reverse case, i.e. for converting costs at any point of time in future, a this factor is used in a reciprocal way and it worth of money is reduced at this rate when bringing it backwards. In MARKAL, as minimization of total discounted system cost is the objective function, this factor becomes most important. Therefore, variation in results with two other values of discount rates has been observed. One on the lower side 6.5% as this rate is equal to the rate of inflation in costs taken in this analysis. This lower rate brings inflation and discount rate equal leading to a situation where effectively there would be no change in costs as the increase in costs due to inflation is equal to the increase in worth of money if forwarded to future time period. This situation is quite possible in future as the interest rates paid by banks in India have come down as compared to the rates few years back. On the other hand the changes in economic conditions of the country may force the banks to revert to higher interest rates as there is a reduction in saving tendency with reduction in interest rates. Therefore, on the higher side 13.5% rate has been considered.

With the low discount rates of 6.5%, equal to the inflation rate, the effect of change in priority with time vanishes as was found and discussed in the base case of section 7.4. Earlier, due to difference in discount rate and inflation rate the model was not finding savings in future more attractive and was the reason of change in priority from small to large hydro in the second period and large hydro to conventional coal in the last period of the simple base case. In this condition, the priority does not change as the discount rates are equal to the inflation and hence small hydro continues to be the best technology without getting affected by time. Similarly the conventional coal based technology is not able to overtake large hydro as the disadvantage of relatively high O&M cost due to fuel costs remains equally important all the time.

In case of high discount rate, 13.5% discount rate makes value of money less important at any future point of time. Therefore small hydro which requires higher initial investment as compared to large hydro does not get any allocation as its advantage of low O&M cost during its life does not get importance due to large discounting. Similarly, the disadvantage of conventional coal power plants does not remain important for future points of time, again due to heavy discounting. Therefore, the model stops allocation to large hydro even after the first period and prefers coal power plants.

Lower Cost of Natural Gas

The present cost of natural gas as compared to coal higher which is restricting it to come into picture. However, in few cases, specially as the emission tax increases, gas has replaced coal based power generation as evident from the results discussed in the previous chapter. There exists a possibility of reduction in prices of natural gas due to the success in the ongoing gas exploration activities. Specially, in some parts of the country, like Rajasthan, there is a good possibility of discovering large reserves. Therefore, prices of gas were lowered by 10% to see the effect on the model. In the base case without taxes, even with the 10% lower prices, gas based power plants found no place. However, in the high tax scenario, with reduction of gas prices, its share was found to increase from the main case where it was appearing only in the last period.

Lower Investment for Gas Power plants

At present the initial investment required for natural gas based power plants are almost same as conventional coal power plants. Most of the parts are made and produced in India itself however, there exists a possibility of reduction in specific investment for gas based power plants due to economy of scale i.e. if more number of units are to be produced, specific costs may come down. Therefore, a possibility of 10% reduction in specific investment related to gas based power plants was considered. The effect of this change was found to be similar to the effect of reducing the prices of gas by 10%. In the base case without taxes, even with the lower investment case, gas based plants found no allocation. There, of course, was an increase allocation in the presence of high taxes as found with lower gas prices.

Higher Rate of Increase for Cost of Coal

There exist huge reserves of coal in the country at present. As about 74% of the power generation at present is based on utilization of coal, it is quite possible to start utilization of deeper and not so convenient coal reserves. This would increase the mining cost of coal which in turn may increase the coal prices at sharper rates. Therefore, a higher rate of increase in coal prices as compared to the inflation cost was considered. Instead of 6.5% inflation in cost, between 8% to 9% rate of price increase, a change in preference of fuel starts and gas based technology replaces the coal based technologies. At further higher rates of price increase, this substitution starts earlier as the total O&M cost of coal plants (including fuel cost) equalizes that cost of gas based plants faster.

Higher Specific Investment for Coal Based Technologies

At present in India not much attention is being paid on de-nitrification of exhaust gases coming out from power plants, but in near future like has been adopted in many other countries, it may become compulsory from the legislation point of view. This would necessitate additional ‘hot gas cleaning’ equipment that are usually not installed in India. Besides, more stringent rules may further increase the exhaust gas treatment and more efficient ash disposal system. These developments may increase the cost of coal based power plants even by 20%. This possibility has been analyzed through the model and it has been found that if there is 10% increase in plant cost the model prefers to have gas based capacity in the high tax case. This replacement takes place even without emission taxes with 20% increase in the plant cost.

Higher Specific Investment Cost for Hydro Power

Rehabilitation and catchment area development for water collection are two complicated issues related to hydro power projects. Rehabilitation activities sometimes bring the project to a standstill which increases the project cost by increasing interest on the huge money that gets locked-in. On the other hand with small hydro projects, plant erection itself is sometimes very complicated due to difficulties in transportation, installation of machinery etc. many activities are therefore to be carried out on the spot. These factor sometimes tend to increase the cost of hydro power projects. To cover these possibilities, an increase of 10% in the investment cost of both the hydro power technologies has been examined. As the reference initial investment of small hydro itself is high, and moreover, in the basic scenario itself it was moving out of the options in later time periods due to the difference of discount rate and inflation rate, the increase in investment moves it out of the options even at the initial periods. However, with the emission taxes, they remain among the preferred technologies even with the elevated costs. Due to this change in the cost structure of small hydro, large hydro gets its share even with the increased costs. In high tax scenario its share remains unaltered due to this price variation.

Additional Hydro Capacity

Looking to the high preference given by the model to hydro power, it was felt necessary to examine the possibility of utilization of additional hydro capacity which is not considered while estimating the economic potential. In India the estimated potential of about 85 GW capacity is corresponding to 60% plant load factor (about 5250 hrs. per year). If the capacity below this economic range is to be considered there maybe two effects. One a lower plant load factor would be available and the other one being increase in specific investment as the construction and other activities would not be as favorable as for the economic sites. Therefore, anew category of plants was introduced having 50% plant load factor (4380 hrs. load duration) and investment requirements 10% higher than the category already considered. The results revealed that this category got no allocation in the case without taxes however, at the high tax rates, it got a minor allocation towards the end.

Additional Wind Capacity

Similar to the additional hydro category, additional wind power category was introduced. Results of the analysis show that this new category of wind power plants having lower plant utilization factor due to lower availability of wind and higher investment requirements due to higher tower heights for finding suitable wind velocity, was not attractive. In both the cases with and without taxes it got no allocation from the model.

Many other variations in the model are possible but the main changes that have a reasonable probability of appearing in real situation have been analyzed in the steps discussed above. Overview of the above sensitivity analysis suggests that the model developed is sufficiently robust as only minor changes are appearing.

Chapter-9

SUMMARY AND CONCLUSIONS

During past few years, in India, there has been an increase in shortage of power supply. Despite efforts from various fronts development of power sector could not achieve the targets. However, various developmental activities are demanding for more and more availability of power and unavailability of power has in fact become a bottleneck for development. On the other hand, the issue of emission of greenhouse gases has already caught fire and various governing agencies in India have already started thinking about possible ways of controlling emission of greenhouse gases. As the power sector is one major contributor towards the total emission of greenhouse gases, there was an urgent need to establish a methodology for addressing both the issues, development of power sector and reduction of greenhouse gas emissions, in a properly linked manner. As several factors in this process are found to have transient effects, dynamic analysis method has been adopted for the work.

Methodological Aspects

There are two different approaches to look at the power sector. One is Energy and Environmental Analysis, in which each technology is examined separately and indicators for its suitability like Cumulative Energy Demand, Energy Yield Ratio, and Emission Coefficient are found to compare various available options. This is usually done through a static approach and does not involve transient effects. The other approach is macroscopic approach more commonly known as the classical Energy Planning approach, which follows a dynamic analysis method by considering time dependent effects like discounting etc. This approach takes financial and performance related parameters related to various technologies simultaneously and finds optimum combination by minimizing the objective function that usually is the overall discounted cost of the system.

As both the approaches have their own importance, it was felt necessary to establish a link between the two. In this work, a new methodology has been formulated to involve dynamic aspects in the existing static approach for Energy Analysis. This has been done through establishing a link between the Cumulative Energy Demand (a system specific, energy analysis parameter of static nature), and the overall energy demand which is a dynamic parameter governed by the rate of growth. With the help of this new method, Cumulative Energy Demand of any system acts as a barrier for growth as it takes away energy from the overall energy pool. Expressions have been derived for finding a maximum rate of growth that balances between this drain and availability of energy. Using this maximum growth rate (a dynamic parameter) based on the results of energy analysis, maximum amount of capacity expansion can be found which is different for each technologies as their to ratio of Cumulative Energy Demands and energy output is plant specific. The value of maximum allowable capacity expansion has been exogenously supplied to the energy planning tool and thus the link between the two different approaches has been established. This work also demonstrates the method for each of the above steps including energy analysis of power generating systems through a combination of process chain analysis and material and energy balance techniques.

For the energy and environmental planning process, as all the parameters and results in this analysis can have values as rational numbers, linear programming method has been found good for finding the optimal solution. A much widely used energy planning software MARKAL (MARket ALlocation), has been used for this purpose. This software provides opportunity to model various energy carriers, technologies, activities, demands with several constraints related to their availability or activity levels through development of a Reference Energy System. With this tool it is even possible to incorporate environmental aspects at various stages and to introduce emission taxes which was one important part of this work. It treats the Reference Energy System as a dynamic bottom-up problem and finds the objective function (minimum discounted system cost) through obtaining a partial equilibrium at all intermediate stages.

The developed methodology of linking Cumulative Energy Demand with energy planning has given another dimension to the conventional energy planning process. However, acceptance of the new method in the energy planning exercises would improve further if there is a direct integration of MARKAL with the results of energy analysis instead of the route of supplying the bounds for growth exogenously. This, of course, necessitates modification in the source code of the software which may be taken-up as one future modification while developing more versatile versions of MARKAL or other similar software.

As another major part of this work, model of the Indian power sector has been developed for MARKAL and several scenarios have been made to cover various major possibilities for the future. Effects of introduction of CO_2 taxes at different rates have also been modeled to find the consequential change in the structure of power sector and to assess the potential for reduction in emissions. Conclusions drawn on the basis of results of these exercises have been presented below.

Interpretation of Results

Modeling of the Indian Power Sector under various scenarios and emission taxes, analysis of their results reveal the following conclusions:

- Hydro power in general, tends to be the first choice for India as almost in every scenario it was given the first allocation.
- While dealing with small hydro technology, it is found to be at an unstable situation in the solutions. At present it is among the preferred technologies but it will continue to remain attractive only if either the discount rates come closer to the inflation rates or emission taxes are introduced.
- Besides hydro power, wind energy is another attractive technology for India and becomes more and more attractive with introduction off emission taxes.
- The effect of technological learning may make small hydro and wind power more attractive over the period of time.

- Due to the cheaper availability of coal, conventional coal based plants are the best choice among all fossil fuel based technology. However, it is not very uneconomic to use PFBC based plants as they had replaced the conventional coal plants with introduction of almost any effect that introduces shadow prices with coal including emission taxes.
- With the objective of reducing CO_2 emissions, taxes can be introduced in the Indian Power Sector. There exists a potential of reducing emissions up to about 25% from the level that is expected to be there in absence of such taxes.
- However, introduction of these taxes changes the power generation strategy. At high tax rates it even finds economic to install extra capacity and not use capacity demanding high taxes if used. Therefore, if the commitment towards reduction of greenhouse gases is firm, it is important to have availability of money so that the system can have additional clean capacity.
- In case this money is not available, it would be better to increase the taxes at slower rates than the rates considered in this analysis. In that condition the model will find a balance between the requirement and availability of money as the increase renewable energy based capacity will be at a slower rate, demanding less money.
- The bound growth scenarios take care of the above condition regarding availability of limited money, to a large extent and control the event of having extra capacity which otherwise is choice of the model.
- These bounds can represent not only economic constraints but also the infrastructure related and cumulative energy demand related constraints which are also to be looked at in any comprehensive planning exercise.
- Coal is usually the most preferred fuel in Indian power sector, but there exists a possibility of replacement of coal by gas as a choice of fuel for power generation. Relative changes in cost of these fuels or investment of plants or introduction of emission taxes bring in this change.
- Due to relatively much higher price of oil, it has no possibility to be the preferred choice over other fuels, coal and gas.
- Technologies like photovoltaic systems and IGCC based power plants do not have any chance to get preference with the scenarios considered. Therefore, more research is necessary to improve the efficiency or to find methods for reduction in specific investments.

Outlook for future

There is relationship between increase in discounted system cost and reduction in emissions is positive. As the reduction in emissions increases it causes some extra cost on the system. From the results it has been found that the increase in total discounted cost of the system for reduction of cumulative CO_2 emissions over the period of this study is around 130 rupees per ton of CO_2 saving with high taxes. This cost gets reduced to about 90 rupees per ton of CO_2 with reference tax case where the potential of reduction in cumulative emissions also gets reduced. These costs are much less as compared to the rates found for other countries like Germany, as the renewable energy based power generation is relatively much cheaper in India. Therefore, targets for reduction in emissions are to be fixed with respect to the capacity of the economy to bear the extra cost of emission reduction. This cost should also be compared with other means of reducing emissions as well. For example, introduction of Compact Fluorescent Lamps (CFL) for lighting would bring some additional cost in the system but would decrease the energy demand. This decrease in demand would in turn bring down the emission level even without introducing emission taxes. Such alternatives are to be weighed with respect to each other before finalization of a nationwide policy for emission reduction.

Robustness of Model and Results:

Observations related to various scenarios and sensitivity analysis done later suggests that positions of many technologies are robust in nature and are not affected much by the most of the variations. Large hydro remains among the first choices in almost all the scenarios and with all the variations except in presence of very high discount rate in comparison with the inflation rate. Wind energy also remain among the preferred technologies with large hydro. The position of small hydro is however, a little more sensitive for the relative change in discount rate and inflation rate. However, with introduction of slight emission taxes, it gains a relatively more robust position in the results. Fossil based technologies usually are preferred by the model after the three renewable energy based technologies. Among them conventional coal and PFBC based power plants have a possibility of mutual replacement. Natural gas based power plants come into picture only at extreme conditions like high taxes and low gas prices. To strike a balance between the fluctuating options between conventional coal and natural gas based systems due to direct or shadow prices, it would be relatively more robust to strike a balance between the two and prefer PFBC based coal power plants. However, there seems to be almost no possibility for a possible preference to oil based, IGCC based and photovoltaic power plants in the solution. The results obtained are not changing drastically by the probable changes as seen in the sensitivity analysis results. Therefore, the model and hence the results can be treated as almost robust model and results respectively.

APPENDICES

LIST OF APPENDICES

APPENDIX-1

Organisations related to planning for the Indian Energy Sector

1. Planning Commission of India – Energy Division
2. Ministry of Power
3. Ministry of Non-Conventional Energy Sources
4. Ministry of Coal
5. Ministry of Petroleum
6. Ministry of Environment an Public Health
7. Central Electricity Authority
8. National Hydro Power Corporation
9. National Thermal Power Corporation
10. Nuclear Power Corporation
11. Electricity Boards of all the states
12. Central Pollution Control Board
13. Power Finance Corporation
14. Indian Renewable Energy Development Agency

APPENDIX-2

Material and energy balance of 1.5 MW Wind Energy Converter

Energy balance of rotorblades

Material	Quantity	Unit	Specific ced(MJ)	ED (material) MJ	Manu. factor	CED (MJ)
Aluminium	33	kg	225.31	7435.39	0.21	8996.82
Fibre glass	2188	kg	50	109400	0.1	120340
Epoxy resin	1516	kg	80	121280	0	121280
Hardener	525	kg	61	32025	0.1	35227.5
Polyamide	76	kg	177.2	13467.2	0	13467.2
Polyethene	228	kg	88.6	20200.8	0	20200.8
PVC-foam	279	kg	66.8	18637.2	0	18637.2
PVC	131	kg	66.8	8750.8	0	8750.8
Paint	184	kg	125	23000	0	23000
Rubber	55	kg	117	6435	0	6435
Others	169	kg	.	10610	0.05	11140.5
Sum	5384	kg		371241.39		387475.82

Energy balance of generator

Material	Quantity	Unit	Specific ced(MJ)	ED (material) MJ	Manu. factor	CED (MJ)
Steel sheet	17927	kg	82	1470014	0.21	1778716.94
Copper	8988	kg	83.9	754093.2	0.1	829502.52
Paint	150	kg	125	18750	0.21	22687.5
Steel (no alloy)	13258	kg	18.362	243443.39	0.15	279959.90
Steel (galvanised, low grade)	105	kg	35.2	3696	0.15	4250.4
Steel (alloy, high grade)	14	kg	42	588	0.15	676.2
Others	248	kg		124569	0.1	137025.9
Sum	40690	kg		2615153.59		3052819.36

Energy balance of rest of machinery

Material	Quantity	Unit	Specific ced(MJ)	ED (material) MJ	Manu. factor	CED (MJ)
Steel (no alloy)	10780	kg	18.36	197942.36	0.15	227633.71
Steel (alloy, low grade)	9101	kg	31	282131	0.15	324450.65
Steel (galvanised, low grade)	1224	kg	35.2	43084.8	0.15	49547.52
Cast steel	3708	kg	61.8	229154.4	0.21	277276.82
Cast iron	21027	kg	17.6	370075.2	0.15	425586.48
Aluminium	127	kg	225.3	28613.1	0.1	31474.41
Copper	293	kg	83.9	24582.7	0.1	27040.97
Fibre glass	924	kg	50	46200	0.21	55902
Unsaturated polyester resin	2159	kg	78	168402	0	168402
Electronics	120	kg	235	28200	0.16	32712
Paint	504	kg	125	63000	0	63000
Others	1624	kg	0	96104	0.05	100909.2
Sum	51591	kg		1577489.56		1783935.76

Energy balance of tower

Material	Quantity	Unit	Specific ced(MJ)	ED (material) MJ	Manu. factor	CED (MJ)
Steel	144182	kg	18.36	2647469.88	0.15	3044590.36
Galvanised steel	4695	kg	22.92	107609.4	0.15	123750.81
Paint	4217	kg	125	527125	0.15	606193.75
Sum	153094	kg		3282204.28		3774534.92

Energy balance of grid connections

Material	Quantity	Unit	Specific ced(MJ)	ED (material) MJ	Manu. factor	CED (MJ)
Galvanised steel	715	kg	22.92	16387.8	0.15	18845.97
Steel (alloy, low grade)	927	kg	31	28737	0.15	33047.55
Steel (alloy, high grade)	630	kg	42	26460	0.21	32016.6
Steel sheet	1300	kg	82	106600	0.1	117260
Steel (for construction)	741	kg	30.1	22304.1	0.15	25649.71
Iron	1042	kg	18.36	19133.20	0	19133.20
Copper	6119	kg	83.9	513384.1	0.1	564722.51
PVC	747	kg	66.8	49899.6	0	49899.6
Gear oil	940	kg	39.4	37036	0	37036
Rest of electricals	1065	kg	100	106500	0.16	123540
Electronics	1283	kg	235	301505	0.16	349745.8
Light weight concrete	12000	kg	2.3	27600	0.21	33396
Others	225	kg		118839	0	118839
Sum	27734	kg		1374385.80		1523131.94

Energy balance of foundation (shallow) for near coastal and inland site

Material	Quantity	Unit	Specific ced(MJ)	ED (material) MJ	Manu. factor	CED (MJ)
Normal concrete	828000	kg	0.7	579600	0.1	637560
Steel (for construction)	24000	kg	30.1	722400	0.15	830760
PVC	166	kg	66.8	11088.8	0	11088.8
Sum	852166	kg		1313088.8		1479408.8

Energy balance of foundation (deep) for coastal site

Material	Quantity	Unit	Specific ced(MJ)	ED (material) MJ	Manu. factor	CED (MJ)
Normal concrete	575000	kg	0.7	402500	0.1	442750
Steel (for construction)	26300	kg	30.1	791630	0.15	910374.5
Steel (no alloy)	13243	kg	18.362	243167.966	0	243167.96
PVC	166	kg	66.8	11088.8	0	11088.8
Sum	614709			1448386.76		1607381.26

APPENDIX-3

Emission balance of 1.5 MW Wind Energy Converter

Emission balance for rotorblades (in grams)

Material	Quantity (kg)	CO_2	CO	SO_2	NOx	CH_4	Particulate
Aluminium	33	395472	320.496	0	0	0	0
Fibre glass	2188	4636547	2780	3050	6632	11014	429
Epoxy resin	1516	5140040	3082	3381	7352	12210	476
Hardener	525	1357271	814	893	1941	3224	126
Polyamide	76	570761	342	375	816	1356	53
Polyethene	228	856142	513	563	1225	2034	79
PVC-foam	279	789874	474	520	1130	1876	73
PVC	131	370873	222	244	530	881	34
Paint	184	974777	584	641	1394	2316	90
Rubber	55	272726	164	179	390	648	25
Sum		15364482	9296	9846	21412	35559	1386

Emission balance for generator (in grams)

Material	Quantity (kg)	CO_2	CO	SO_2	NOx	CH_4	Particulate
Steel sheet	17927	124249087	1719633	185253	118485	0	38588
Copper	8988	59770200	62916	100216	283392	62916	2067240
Paint	150	794655	476	523	1137	1888	74
Steel (no alloy)	13258	20576416	284782	30679	19622	0	6390
Steel (galvanised, low grade)	105	312395	4324	466	298	0	97
Steel (alloy, high grade)	14	49699	688	74	47	0	15
Sum		205752451	2072819	317211	422980	64804	2112404

Emission balance for rest of housing (in grams)

Material	Quantity (kg)	CO_2	CO	SO_2	NOx	CH_4	Particulate
Steel (no alloy)	10780	16730560	231554	24945	15954	0	5196
Steel (alloy, low grade)	9101	23846385	330039	35554	22740	0	7406
Steel (galvanised, low grade)	1224	3641630	50401	5430	3473	0	1131
Cast steel	3708	19368676	268066	28878	18470	0	6015
Cast iron	21027	31279638	432917	46637	29829	0	9714
Aluminium	127	1521968	1233	0	0	0	0
Copper	293	1948450	2051	3267	9238	2051	67390
Fibre glass	924	1958030	1174	1288	2801	4651	181
Unsaturated polyester resin	2159	7137146	4280	4694	10209	16954	661
Electronics	120						
Paint	504	2670041	1601	1756	3819	6343	247
Sum		110102522	1323316	152450	116533	29999	97942

Emission balance for tower (in grams)

Material	Quantity (kg)	CO_2	CO	SO_2	NOx	CH_4	Particulate
Steel	144182	223770464	3097029	333637	213389	0	69496
Galvanised steel	4695	9095403	125882	13561	8673	0	2825
Paint	4217	22340399	13396	14694	31956	53069	2069
Sum		255206266	3236307	361892	254018	53069	74389

Emission balance for grid connections (in grams)

Material	Quantity (kg)	CO_2	CO	SO_2	NOx	CH_4	Particulate
Galvanised steel	715	1385136	19171	2065	1321	0	430
Steel (alloy, low grade)	927	2428920	33617	3621	2316	0	754
Steel (alloy, high grade)	630	2236462	30953	3335	2133	0	695
Steel sheet	1300	9010086	124701	13434	8592	0	2798
Steel for construction	741	1885196	26091	2811	1798	0	585
Iron	1042	1617184	22382	2411	1542	0	502
Copper	6119	40691350	42833	68227	192932	42833	1407370
PVC	747	2114825	1268	1391	3025	5024	196
Gear oil	940	940					
Rest of electricals	1065	9356332	2671	16021	2871	412	4030
Electronics	1283	26488084	7561	45355	8128	1168	11409
Light weight concrete	12000	2424740	692	4152	744	107	1044
Sum		99639254	311941	162822	225402	49544	1429815

Emission balance for foundation (in grams)

Material	Quantity (kg)	CO_2	CO	SO_2	NOx	CH_4	Particulate
Normal concrete	828000	50919532	14536	87188	15625	2244	21933
Steel for construction	24000	61058970	845069	91038	58226	0	18963
PVC	166	469961	282	309	672	1116	44
Sum		61528931	859886	178535	74523	3361	40939

APPENDIX-4

Material balance of 4X210 MW coal power plant

Section	Sub-section	Component	Amount used	Unit
Mechanical Equipment	**Unit equipment**	Steam turbine & condensor	3494400	kg.
		Regeneration unit	841600	kg.
		Turbine piping, supports (High pressure)	320000	kg.
		Turbine piping, supports (Low pressure)	540000	kg.
		Steam boiler, frame, piping, blowers	29600000	kg.
		Induced & forced draft fans, motors	957600	kg.
		Valves	163200	kg.
		Feed-cum-de-aeration plant (tank, condenser, pump, motor)	585600	kg.
		Superheating plant	46400	kg.
		Oil coolers, purifiers, lube pumps,motors	146400	kg.
		Boiler room ancillary equipment (flash tank, water coolers, air heaters, drain pumps, motors	86000	kg.
		Hydrazine-ammonia plant (pump, motors)	1780	kg.
		Unit piping, valves, flanges, supports (high pressure)	2260000	kg.
		Unit piping, valves, flanges, supports (low pressure)	2136000	kg.
		Boiler ancillary equipment (non-std. Equipment, Gen. Set., packing material etc)	2800000	kg.
		Pipelines	1600000	kg.
	Total		**45578980**	**kg.**
	Common station equipment	Blowers, lube pumps, ash water pumps, motors, water pumps	90100	kg.
		Hoisting equipment (cranes, lift)	302100	kg.
		Common piping with valves, supports (high pressure)	90000	kg.
		Common piping with valves, supports (low pressure)	163500	kg.
		Non-standard equipment	16000	kg.
	Total		**661700**	**kg.**
	Fuel oil facilities	Fuel oil equipment (oil coolers, heaters, tanks, pumps, motors)	63500	kg.
		High pressure piping, valves, supports	6000	kg.
		Low pressure piping, valves, supports	403000	kg.
		Non-standard equipment	35500	kg.
	Total		**508000**	**kg.**
	Central lube oil facilities	Oil pumps, motors, tanks, piping	12000	kg.
	Total		**12000**	**kg.**
	H2 & CO2 plant	Non-standard equipment	500	kg.
		High pressure piping, valves, support	300	kg.
		Low pressure piping, valves, support	10800	kg.
	Total		**11600**	**kg.**
	Common compressor plant	Piston-type compressor, air reciever, motors, pumps	29000	kg.
		Low pressure piping, valves, support	16600	kg.
		Non-standard equipment	4500	kg.
	Total		**50100**	**kg.**

	Interplant trestles	High pressure piping on trestles, valves, supports	20000	kg.
		Low pressure piping on trestles, valves, supports	120000	kg.
	Total		**140000**	**kg.**
Hydro-technical equipment	**Cold water pump house no.1**	Centrigugal pumps with motor	258440	kg.
		Common equipment (screen washing pump, water-intake & emptying pump)	1652	kg.
		Hoisting equipment	17600	kg.
		Water intake structure, stainers, trash racks	22450	kg.
		Travelling screens with electric drives	47200	kg.
		Pipings, valves, fixtures	19450	kg.
		Check valves, expansion joints	22410	kg.
	Total		**389202**	**kg.**
	Cold water pump house no.2	Centrigugal pumps with motor	258440	kg.
		Common equipment (screen washing pump, water-intake & emptying pump)	1652	kg.
		Hoisting equipment	17600	kg.
		Water intake structure, stainers, trash racks	22450	kg.
		Travelling screens with electric drives	47200	kg.
		Pipings, valves, fixtures	19450	kg.
		Check valves, expansion joints	22410	kg.
	Total		**389202**	**kg.**
Ash disposal system	**Ash-slurry pump house no.1**	Dredge pumps with motor	90000	kg.
		Gland seal pump with motor	1680	kg.
		Pipings, valves, fixtures	30000	kg.
	Total		**121680**	**kg.**
	Ash-slurry pump house no.2	Dredge pumps with motor	90000	kg.
		Gland seal pump with motor	1680	kg.
		Pipings, valves, fixtures	30000	kg.
	Total		**121680**	**kg.**
	Fly-ash pump house	Dredge pumps with motor	66400	kg.
		Gland seal pumps with motor	840	kg.
		Piping, valves, fixtures	36900	kg.
	Total		**104140**	**kg.**
	Fly/bottom ash disposal pipes	**Carbon steel pipes (hot deformed seamless) 273X11mm dia.**	**1137200**	**kg.**
		Carbon steel pipes (hot deformed seamless) 426X10mm dia.	1231100	kg.
	Total		**2368300**	**kg.**
Electrical equipment		Hydrogen-water cooled TG, excitation system	1224000	kg.
		40 MVA 3-phase transformer	288000	kg.
		60 MVA 3-phase transformer	216000	kg.
		Transformer oil	26000	kg.
		1000 kVA 3-phase transformer	56000	kg.
		6.6 kV switchgears	403900	kg.
		Busducts	340060	kg.
		415 kV switchgears and protection transformers, panels, control cabinets	231830	kg.
		Copper conductor power cables	31850	kg.

		Copper conductor control cables	750	kg.
		Steelwork structures for installation	8200	kg.
		Steel articles for chimney & electrical equipment	4160	kg.
		Fuel oil related equipment (switchgear, steel articles)	27000	kg.
		Hydrogen generation plant electrolizers, electrical equipment	58830	kg.
		Station compressor plant electrical equipment and steel articles	500	kg.
		Outdoor transformer and installation material	300	kg.
		low voltage equipment & steel articles for pump house	2200	kg.
		Low voltage equipment & steel articles for ash slurry pump house	1040	kg.
		Instrumentation for pre-starting	8000	kg.
		Low voltage equipment for fly ash pump house	500	kg.
	Total		**2929120**	**kg.**
Instrumentation & Control Equipment		Automatic control system, process monitoring for main plant	156100	kg.
		Low voltage devices for main plant including control panels with hardware	254660	kg.
		Articles for erection of control station station, stands	56000	kg.
		C&I equipment for chimney	100	kg.
		C&I equipment for fuel oil plant	6940	kg.
		C&I equipment for H2/CO2 plant	120	kg.
		C&I equipment for compressor plant	480	kg.
		Copper conductor control cables	5700	kg.
		C&I equipment for pump house no.1	5700	kg.
		C&I equipment for pump house no.2	5700	kg.
		C&I equipment for ash slurry pump house no.1	3580	kg.
		C&I equipment for ash slurry pump house no.2	3580	kg.
		C&I equipment for fly ash pump house	2540	kg.
		Instrumentation for commissioning	1500	kg.
	Total		**502700**	
Civil structural steelworks		TG hall & deaerator bay framework (flooring, beams, wall support structures)	5870000	kg.
		Light weight panels of TG hall & deaerator bay roof	530000	kg.
		TG hall, gable ends, switchgear rooms, stairs, gangways and lateral beams for piping	340000	kg.
		Plateforms for TG hall for maintenance, foundations	1475000	kg.
		Framework of high frequency excitation rooms	160000	kg.
		Framework of miscellaneous pump house	199300	kg.
		Condensate storage tank	196000	kg.
		Supporting structure for maintenance plateforms of process equipment	1730000	kg.
		Bioler shelters, lift wells wit hsheeting, staircase	2922000	kg.
		Framework of bunker gallary & transfer tower, floor beams, secondary beams	3875000	kg.
		R.C. bunkers	1020000	kg.
		Supporting structures for process equipment	860000	kg.
		Flue gas ducts	1327000	kg.

		Upper part of chimney flues	200000	kg.
		Structure of fuel oil handling facilities (pumphouse, wall supports, partitions, tanks	580000	kg.
		Framework of H2 & CO2 plant building, wall support framed structures	85000	kg.
		Framework of compressor plant building, wall support framed structures	65000	kg.
		Trestles of interplant pipelines	220000	kg.
	Total		**21654300**	**kg.**
Hydrotechnical structures: civil part	**Pump house no.1& 2**	Framework of external wall supporting framed structure	315720	kg.
		Light weight roof treatment	13600	kg.
		Monorails of hoisting equipment	4900	kg.
		Steel hardwares	11320	kg.
	Total		**345540**	**kg.**
	Ash-disposal system: bottom ash pump house no.1& 2	Framework of external wall supporting framed structure	399860	kg.
		Overhead crane track	16000	kg.
		Light weight roof treatment	32000	kg.
		Steel hardwares	12600	kg.
	Total		**460460**	**kg.**
	Ash-disposal system: fly ash pump house	Framework of external wall supporting framed structure	210000	kg.
		Overhead crane track	8000	kg.
		Light weight roof treatment	16000	kg.
		Steel hardwares	6000	kg.
	Total		**240000**	**kg.**
	Grand total		**76588704**	**kg.**

APPENDIX-5

Details of dynamic energy analysis calculations

Case1: Total reinvestment of energy output for capacity expansion

	CED MWh/MW$_{el}$	Equivalent CED GJ/MW$_{el}$	Share of electricity (fraction)	CED$_{el}$ GJ/MW$_{el}$	Annual output GJ$_{el}$/MW	Primary Equivalent of annual output GJ/MW	Const. Time (yrs)	Maximum annual growth (%)
SPV (Mono crystalline)	12500	45000	0.8	36000	4730.4	13515.43	1	31.87
SPV (Poly crystalline)	9500	34200	0.8	27360	4730.4	13515.43	1	40.14
SPV (Amorphous)	6500	23400	0.8	18720	4730.4	13515.43	1	54.34
Wind(small)	2500	9000	0.3	2700	12614.4	36041.14	0.6	443.94
Wind(large)	1500	5400	0.3	1620	12614.4	36041.14	1	314.62
Hydro(large)	6500	23400	0.5	11700	18921.6	54061.71	7	24.66
Hydro(small)	6000	21600	0.5	10800	18921.6	54061.71	3	59.75
Coal (advanced)	1200	4320	0.5	2160	20183.04	57665.83	4	83.03
Coal (moderate)	1000	3600	0.5	1800	20183.04	57665.83	4	87.44
Coal (basic)	800	2880	0.5	1440	20183.04	57665.83	4	92.86
Gas(combined cycle)	900	3240	0.5	1620	20183.04	57665.83	3	119.99
Gas(simple cycle)	500	1800	0.5	900	20183.04	57665.83	2	208.77

Case 2: Partial reinvestment of energy output for capacity expansion

	CED MWh/MW_{el}	Equivalent CED GJ/MW_{el}	Share of electricity (fraction)	CED_{el} GJ/MW_{el}	Annual output GJ_{el}/MW	Primary Equivalent of annual output GJ/MW	Const. Time (yrs)	Re-investment factor	Maximim annual in growth (%)
SPV(Mono crystalline)	12500	45000	0.8	36000	4730.4	13515.43	1	0.2	7.24
SPV(Poly crystalline)	9500	34200	0.8	27360	4730.4	13515.43	1	0.2	9.42
SPV(Amorphous)	6500	23400	0.8	18720	4730.4	13515.43	1	0.2	13.48
Wind(small)	2500	9000	0.3	2700	12614.4	36041.14	0.6	0.2	216.68
Wind(large)	1500	5400	0.3	1620	12614.4	36041.14	1	0.2	169.55
Hydro(large)	6500	23400	0.5	11700	18921.6	54061.71	7	0.2	9.35
Hydro(small)	6000	21600	0.5	10800	18921.6	54061.71	3	0.2	23.12
Coal(advanced)	1200	4320	0.5	2160	20183.04	57665.83	4	0.2	46.17
Coal(moderate)	1000	3600	0.5	1800	20183.04	57665.83	4	0.2	50.06
Coal(basic)	800	2880	0.5	1440	20183.04	57665.83	4	0.2	54.95
Gas(combined cycle)	900	3240	0.5	1620	20183.04	57665.83	3	0.2	69.80
Gas(simple)	500	1800	0.5	900	20183.04	57665.83	2	0.2	131.28

APPENDIX-6

Year wise demand and supply of electricity from public utilities in India

Year	Power Demand in GWh	Power Supply in GWh
1980-81	120118	103734
1981-82	129245	113928
1982-83	136849	121311
1983-84	145284	130122
1984-85	155432	145393
1985-86	170746	157301
1986-87	192356	157301
1987-88	210993	187873
1988-89	223194	206326
1989-90	247762	228784
1990-91	267632	246941
1991-92	288974	269136
1992-93	305266	282384
1993-94	323252	303681
1994-95	352260	329255
1995-96	389721	356441
1996-97	413490	371395

Source [CMIE 2000]

APPENDIX-7

Share of different sectors of Indian economy in electricity consumption

Year	Agriculture	Industrial	Transport	Domestic	All Others	T&D loss
1980-81	14489	48069	2266	9246	3614	21325
1981-82	15201	53064	2505	10440	3822	23589
1982-83	17817	52968	2633	12092	4234	25644
1983-84	18234	57095	2710	13235	4511	27689
1984-85	20960	63019	2880	15506	4765	31214
1985-86	23422	66980	3082	17258	4967	34194
1986-87	29444	70297	3229	19323	5887	37784
1987-88	35267	69180	3616	22120	6589	42231
1988-89	38878	75412	3772	24768	7452	46032
1989-90	44056	80695	4070	29577	7474	53260
1990-91	50321	84209	4112	31982	8552	56521
1991-92	58557	87288	4520	35854	9394	61439
1992-93	63328	90169	5068	39717	9739	61565
1993-94	70699	94504	5620	43344	10258	65010
1994-95	79301	100126	5886	47916	10429	69569
1995-96	85732	104693	6223	51733	11651	79363
1996-97	84019	104165	6594	55267	12642	91105

APPENDIX-8

Share of various technologies in power generation capacity and electricity generation in India

Share of technologies in total power generation capacity as public utilities (in MW)

Year	Total Capacity	Hydro	Thermal*	Coal thermal	Oil thermal	Gas thermal	Nuclear
1990-91	66086	18753	45768	43004	212	2552	1565
1991-92	69065	19194	48086	44791	199	3095	1785
1992-93	72330	19576	50749	46597	224	3928	2005
1993-94	76753	20379	54369	49147	339	4883	2005
1994-95	81171	20833	58114	52139	343	5632	2225
1995-96	83294	20986	60083	53479	335	6268	2225
1996-97	85795	21658	61912	54154	1196	6562	2225
1997-98	89167	21891	65051	55969	1276	7805	2225
1998-99	93249	22438	68586	57929	1566	9090	2225

*Figures for thermal power include wind capacity as wind-diesel plants

Share of technologies in total generated power from utilities (in GWh)

Year	Gross generation	Hydro	Thermal	Coal thermal	Oil thermal	Gas thermal	Nuclear	Net power available**
1990-91	264329	71641	186546	178322	111	8113	6141	246941
1991-92	287029	72757	208747	197163	134	11450	5524	269136
1992-93	301362	69869	224766	211124	162	13480	6726	282384
1993-94	324050	70463	248189	233151	311	14728	5398	303681
1994-95	350490	82712	262130	243110	545	18475	5648	329255
1995-96	379877	72579	299316	273744	714	24858	7982	356441
1996-97	395889	68901	317918	289378	1554	26985	9071	371395
1997-98	421320	74571	336654	N.Avb.	N.Avb.	N.Avb.	10095	N.Avb.
1998-99	448406	82619	353800	N.Avb.	N.Avb.	N.Avb.	11987	N.Avb.

*Figures for thermal power include wind capacity as wind-diesel plants,

** Net power = Gross power – internal consumption + purchase from captive plants

N.Avb.: Break-up not available

APPENDIX-9

Properties of different grades of coal in India

Grade	UHV (kcal/kg)		Ash Content (%)		GCV (kcal/kg)	
	From	To	From	To	From	To
A	6200	above 6200	below 13.56	13.56	6406	above 6406
B	5600	6200	13.56	17.91	5997	6406
C	4940	5600	17.91	22.69	5447	5997
D	4200	4940	22.69	28.06	5042	5447
E	3360	4200	28.06	34.14	4469	5042
F	2400	3360	34.14	41.1	3814	4469
G	1300	2400	41.1	49.07	3064	3814

Source: [TEDDY 2000]

APPENDIX-10

Availability of crude oil in India from different sources

Supply of crude oil in India (thousand tonnes)

Year	Production	Imports	Availability	Crude throughput
1980-81	10507	16248	26755	25836
1981-82	16194	15298	31492	30146
1982-83	21063	16949	38012	33156
1983-84	26020	15967	41987	35263
1984-85	28990	13642	42632	35556
1985-86	30168	15144	45312	42910
1986-87	30480	15476	45956	45477
1987-88	30357	17732	48089	47754
1988-89	32040	17815	49855	48803
1989-90	34087	19490	53577	51943
1990-91	33021	20699	53720	51772
1991-92	30346	23994	54340	51423
1992-93	26950	29247	56197	53482
1993-94	27026	30822	57848	54296
1994-95	32239	27349	59588	56534
1995-96	35167	27342	62509	58741
1996-97	32901	33906	66807	62870
1997-98	33859	34494	68353	65166
1998-99	32723	39808	72531	68538

APPENDIX-11

Consumption and price variation of different oil products in power sector

Consumption of oil-products in power generation through utilities (thousand tonnes)

Year	High speed diesel (HSD)	Light Diesel Oil	Furnace Oil	Low sulphur heavy stock (LSHS)
1980-81	194	158	903	1182
1981-82	177	178	629	1136
1982-83	226	216	833	1191
1983-84	145	219	952	1273
1984-85	140	233	1032	1462
1985-86	160	255	804	1526
1986-87	161	273	712	1489
1987-88	209	251	636	1659
1988-89	132	346	617	1571
1989-90	126	325	692	1630
1990-91	104	282	531	1835
1991-92	110	230	527	1798
1992-93	108	211	555	1779
1993-94	115	182	490	1676
1994-95	229	165	580	1624
1995-96	167	166	720	1747
1996-97	226	184	764	1634

Price variation of different petroleum products (Rs./unit)

Year	HSD ('000 lt.)	Light Diesel Oil ('000 lt.)	Furnace oil ('000 lt.)	LSHS (tonnes)
25/7/1991	4542	4199	3992	3461
16/9/1992	5539	5396	4989	3807
2/2/94	6289	6146	4989	4804
1/3/94	5717	5588	4535	4804
7/7/96	6575	7264	5896	4804
2/9/97	8375	7264	5143	6245
17/1/1998	8375	7264	5053	6089
1/4/98	7839	7201	4801	5452
3/6/98	7537	7201	4801	5071
1/1/99	6722	6300	4810	NA
28/2/1999	6622	6300	4050	NA

APPENDIX-12

Availability and consumption of natural gas in India

Reserves, production and utilisation of natural gas (million cubic meters)

Year	Total reserves	Gross Production	Net production	Consumption by Power utilities	% for power utilities
1980-81	410650	2358	1522	492	32.32
1981-82	419890	3851	2222	612	27.54
1982-83	475260	4936	2957	1025	34.66
1983-84	478250	5961	3399	1209	35.56
1984-85	478630	7241	4141	1454	35.11
1985-86	497050	8134	4950	1299	26.24
1986-87	540810	9853	7072	2041	28.86
1987-88	579470	11467	7968	2721	34.14
1988-89	647550	13217	9250	1823	19.70
1989-90	686450	16988	11172	2140	19.15
1990-91	729790	17998	12766	3634	28.46
1991-92	735460	18645	14441	4774	33.05
1992-93	717950	18060	16116	4967	30.82
1993-94	706690	18335	16340	4785	29.28
1994-95	659640	19381	17339	5229	30.15
1995-96	640140	22639	21202	6836	32.24
1996-97	692000	23255	21495	6935	32.26
1997-98	675000	26401	24522	8114	33.08
1998-99	648000	27428	25716	8714	33.88

APPENDIX-13

Growth of power generation capacity* in the base case scenario (with and without emission taxes)

Base case without taxes

	Base yr.	**2000-2005**	**2005-2010**	**2010-2015**	**2015-2020**	**2020-2025**
Conventional coal	55.97	55.97	55.97	55.97	65.04	90.33
Large Hydro	21.89	34.39	49.3	67.7	85	85
Small Hydro	0.5	20	20	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	0.4	0.4
Wind	1.5	1.5	20	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Base case with low tax

	Base yr.	**2000-2005**	**2005-2010**	**2010-2015**	**2015-2020**	**2020-2025**
Conventional coal	55.97	55.97	55.97	55.97	65.04	90.33
Large Hydro	21.89	34.93	49.3	67.7	85	85
Small Hydro	0.5	20	20	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	0.4	0.4
Wind	1.5	1.5	20	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Base case with moderate tax

	Base yr.	**2000-2005**	**2005-2010**	**2010-2015**	**2015-2020**	**2020-2025**
Conventional coal	55.97	55.97	55.97	55.97	65.04	65.04
Large Hydro	21.89	34.93	49.85	67.7	85	85
Small Hydro	0.5	20	20	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	0.4	22.88
Wind	1.5	1.5	20	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Base case with reference tax

	Base yr.	**2000-2005**	**2005-2010**	**2010-2015**	**2015-2020**	**2020-2025**
Conventional coal	55.97	55.97	55.97	55.97	65.04	65.04
Large Hydro	21.89	77.11	77.11	77.11	85	85
Small Hydro	0.5	20	20	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	0.4	22.88
Wind	1.5	1.5	20	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Base case with high tax

	Base yr.	**2000-2005**	**2005-2010**	**2010-2015**	**2015-2020**	**2020-2025**
Conventional coal	55.97	55.97	55.97	55.97	55.97	55.97
Large Hydro	21.89	85	85	85	85	85
Small Hydro	0.5	20	20	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	8.69	8.69
Wind	1.5	1.5	20	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

*Others: sum of Nuclear, IGCC, Oil, PV based power generation capacities; * all capacities are in GW*

APPENDIX-14

Growth of power generation capacity* in the learning technologies scenario (with and without emission taxes)

Learning Technologies Scenario without tax

	Base yr.	**2000-2005**	**2005-2010**	**2010-2015**	**2015-2020**	**2020-2025**
Conventional coal	55.97	55.97	55.97	55.97	65.04	65.04
Large Hydro	21.89	45.57	60.22	67.7	85	85
Small Hydro	0.5	0.5	0.5	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	0.4	22.88
Wind	1.5	1.5	20	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Learning Technologies Scenario with low tax

	Base yr.	**2000-2005**	**2005-2010**	**2010-2015**	**2015-2020**	**2020-2025**
Conventional coal	55.97	55.97	55.97	55.97	65.04	65.04
Large Hydro	21.89	45.57	60.22	67.7	85	85
Small Hydro	0.5	0.5	0.5	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	0.4	22.88
Wind	1.5	1.5	20	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Learning Technologies Scenario with moderate tax

	Base yr.	**2000-2005**	**2005-2010**	**2010-2015**	**2015-2020**	**2020-2025**
Conventional coal	55.97	55.97	55.97	55.97	65.04	65.04
Large Hydro	21.89	53.89	67.7	67.7	85	85
Small Hydro	0.5	0.5	1.61	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	0.4	22.88
Wind	1.5	1.5	20	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Learning Technologies Scenario with reference tax

	Base yr.	**2000-2005**	**2005-2010**	**2010-2015**	**2015-2020**	**2020-2025**
Conventional coal	55.97	55.97	55.97	55.97	55.97	55.97
Large Hydro	21.89	54.43	69.35	76.54	85	85
Small Hydro	0.5	0.5	0.5	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	8.69	30.95
Wind	1.5	1.5	20	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Learning Technologies Scenario with reference tax

	Base yr.	**2000-2005**	**2005-2010**	**2010-2015**	**2015-2020**	**2020-2025**
Conventional coal	55.97	55.97	55.97	55.97	55.97	55.97
Large Hydro	21.89	85	85	85	85	85
Small Hydro	0.5	20	20	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	30.06
PFBC	0.5	0.4	0.4	0.4	8.69	8.69
Wind	1.5	1.5	20	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Others: sum of Nuclear, IGCC, Oil, PV based power generation capacities; * *all capacities are in GW*

APPENDIX-15

Growth of power generation capacity* in the bound growth scenario (with and without emission taxes)

Bound Growth Scenario without tax

	Base yr.	2000-2005	2005-2010	2010-2015	2015-2020	2020-2025
Conventional coal	55.97	60.98	60.98	60.98	71.09	96.38
Large Hydro	21.89	31.89	47.59	68.8	85	85
Small Hydro	0.5	5.5	13.55	13.55	13.55	13.55
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	0.4	0.4
Wind	1.5	6.5	14.55	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Bound Growth Scenario with low tax

	Base yr.	2000-2005	2005-2010	2010-2015	2015-2020	2020-2025
Conventional coal	55.97	60.48	60.48	60.48	65.04	90.33
Large Hydro	21.89	31.89	47.59	62.88	85	85
Small Hydro	0.5	5.5	13.55	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	0.4	0.4
Wind	1.5	6.5	14.55	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Bound Growth Scenario with moderate tax

	Base yr.	2000-2005	2005-2010	2010-2015	2015-2020	2020-2025
Conventional coal	55.97	60.48	60.48	60.48	65.04	65.04
Large Hydro	21.89	31.89	47.59	62.88	85	85
Small Hydro	0.5	5.5	13.55	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	0.4	22.88
Wind	1.5	6.5	14.55	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Bound Growth Scenario with reference tax

	Base yr.	2000-2005	2005-2010	2010-2015	2015-2020	2020-2025
Conventional coal	55.97	58.6	58.6	58.6	65.04	65.04
Large Hydro	21.89	31.89	47.59	72.26	85	85
Small Hydro	0.5	5.5	13.55	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	0.4	22.88
Wind	1.5	6.5	14.55	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Bound Growth Scenario with high tax

	Base yr.	2000-2005	2005-2010	2010-2015	2015-2020	2020-2025
Conventional coal	55.97	58.6	58.6	58.6	58.6	58.6
Large Hydro	21.89	31.89	47.59	72.26	85	85
Small Hydro	0.5	5.5	13.55	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	6.29	6.29
Wind	1.5	6.5	14.55	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Others: sum of Nuclear, IGCC, Oil, PV based power generation capacities; * *all capacities are in GW*

APPENDIX-16

Growth of power generation capacity* in the bound with learning technologies scenario (with and without emission taxes)

Bound Growth with Learning Technology Scenario without tax

	Base yr.	**2000-2005**	**2005-2010**	**2010-2015**	**2015-2020**	**2020-2025**
Conventional coal	55.97	60.48	60.48	60.48	65.04	65.04
Large Hydro	21.89	31.89	47.59	62.88	85	85
Small Hydro	0.5	5.5	11.55	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	0.4	22.88
Wind	1.5	6.5	14.55	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Bound Growth with Learning Technology Scenario with low tax

	Base yr.	**2000-2005**	**2005-2010**	**2010-2015**	**2015-2020**	**2020-2025**
Conventional coal	55.97	60.48	60.48	60.48	65.04	65.04
Large Hydro	21.89	31.89	47.59	62.88	85	85
Small Hydro	0.5	5.5	11.55	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	0.4	22.88
Wind	1.5	6.5	14.55	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Bound Growth with Learning Technology Scenario with moderate tax

	Base yr.	**2000-2005**	**2005-2010**	**2010-2015**	**2015-2020**	**2020-2025**
Conventional coal	55.97	58.6	58.6	58.6	65.04	65.04
Large Hydro	21.89	31.89	47.59	64.89	85	85
Small Hydro	0.5	5.5	13.55	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	0.4	22.88
Wind	1.5	6.5	14.55	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Bound Growth with Learning Technology Scenario with reference tax

	Base yr.	**2000-2005**	**2005-2010**	**2010-2015**	**2015-2020**	**2020-2025**
Conventional coal	55.97	58.6	58.6	58.6	58.6	58.6
Large Hydro	21.89	31.89	47.59	72.26	85	85
Small Hydro	0.5	5.5	13.55	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	7.81
PFBC	0.5	0.4	0.4	0.4	6.29	28.61
Wind	1.5	6.5	14.55	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Bound Growth with Learning Technology Scenario with high tax

	Base yr.	**2000-2005**	**2005-2010**	**2010-2015**	**2015-2020**	**2020-2025**
Conventional coal	55.97	55.97	55.97	55.97	55.97	55.97
Large Hydro	21.89	31.89	47.59	72.26	85	85
Small Hydro	0.5	5.5	13.55	20	20	20
Natural gas	7.81	7.81	7.81	7.81	7.81	30.06
PFBC	0.5	0.4	0.4	0.4	8.69	8.69
Wind	1.5	6.5	14.55	20	20	20
Others	3.7	6.5	11.5	16.5	21.5	26.5

Others: sum of Nuclear, IGCC, Oil, PV based power generation capacities ; * *all capacities are in GW*

APPENDIX-17

Unused capacity level of power plants as suggested by MARKAL

Base case scenario (with and without taxes)

Conventional coal power plants

	Unused capacity (%) 2000-2005	Unused capacity (%) 2005-2010	Unused capacity (%) 2010-2015	Unused capacity (%) 2015-2020	Unused capacity (%) 2020-2025
Plant availability factor (%)	64	64	64	64	64
No tax case	0	0	0	0	0
Low tax case	0	0	0	0	0
Moderate tax case	0	0	0	0	0
Reference tax case	45.22	29.22	0	0	0
High tax case	53.68	37.68	8.46	0	0

Natural gas based power plants

	Unused capacity (%) 2000-2005	Unused capacity (%) 2005-2010	Unused capacity (%) 2010-2015	Unused capacity (%) 2015-2020	Unused capacity (%) 2020-2025
Plant availability factor (%)	64	64	64	64	64
No tax case	64	64	0	0	0
Low tax case	64	64	0	0	0
Moderate tax case	64	64	0	0	0
Reference tax case	64	64	64	0	0
High tax case	64	64	64	0	0

Nuclear power plants

	Unused capacity (%) 2000-2005	Unused capacity (%) 2005-2010	Unused capacity (%) 2010-2015	Unused capacity (%) 2015-2020	Unused capacity (%) 2020-2025
Plant availability factor (%)	75	75	75	75	75
No tax case	75	75	75	75	75
Low tax case	75	75	75	75	75
Moderate tax case	75	75	75	75	75
Reference tax case	75	75	75	75	75
High tax case	75	75	75	75	10.91

Learning technology scenario

Conventional coal power plants

	Unused capacity (%) 2000-2005	Unused capacity (%) 2005-2010	Unused capacity (%) 2010-2015	Unused capacity (%) 2015-2020	Unused capacity (%) 2020-2025
Plant availability factor (%)	64	64	64	64	64
No tax case	0	0	0	0	0
Low tax case	0	0	0	0	0
Moderate tax case	0	0	0	0	0
Reference tax case	0	0	0	0	0
High tax case	53.68	37.68	8.46	0	0

Natural gas based power plants

	Unused capacity (%) 2000-2005	Unused capacity (%) 2005-2010	Unused capacity (%) 2010-2015	Unused capacity (%) 2015-2020	Unused capacity (%) 2020-2025
Plant availability factor (%)	64	64	64	64	64
No tax case	0	0	0	0	0
Low tax case	0	0	0	0	0
Moderate tax case	64	64	0	0	0
Reference tax case	64	64	64	0	0
High tax case	64	64	64	0	0

Nuclear power plants

	Unused capacity (%) 2000-2005	Unused capacity (%) 2005-2010	Unused capacity (%) 2010-2015	Unused capacity (%) 2015-2020	Unused capacity (%) 2020-2025
Plant availability factor (%)	75	75	75	75	75
No tax case	75	75	75	75	75
Low tax case	75	75	75	75	75
Moderate tax case	75	75	75	75	75
Reference tax case	75	75	75	75	75
High tax case	75	75	75	75	75

Bound Growth Scenario

Conventional coal power plants

	Unused capacity (%) 2000-2005	Unused capacity (%) 2005-2010	Unused capacity (%) 2010-2015	Unused capacity (%) 2015-2020	Unused capacity (%) 2020-2025
Plant availability factor (%)	64	64	64	64	64
No tax case	0	0	0	0	0
Low tax case	0	0	0	0	0
Moderate tax case	0	0	0	0	0
Reference tax case	0	0	0	0	0
High tax case	0	0	0	0	0

Natural gas based power plants

	Unused capacity (%) 2000-2005	Unused capacity (%) 2005-2010	Unused capacity (%) 2010-2015	Unused capacity (%) 2015-2020	Unused capacity (%) 2020-2025
Plant availability factor (%)	64	64	64	64	64
No tax case	0	19.5	0	0	0
Low tax case	0	15.4	0	0	0
Moderate tax case	0	15.4	0	0	0
Reference tax case	0	0	64	0	0
High tax case	0	0	62.09	0	0

Nuclear power plants

	Unused capacity (%) 2000-2005	Unused capacity (%) 2005-2010	Unused capacity (%) 2010-2015	Unused capacity (%) 2015-2020	Unused capacity (%) 2020-2025
Plant availability factor (%)	75	75	75	75	75
No tax case	75	75	75	75	75
Low tax case	75	75	75	75	75
Moderate tax case	75	75	75	75	75
Reference tax case	50.96	75	75	75	75
High tax case	44.56	75	75	75	10.72

Bound growth with learning technologies scenario

Conventional coal power plants

	Unused capacity (%) 2000-2005	Unused capacity (%) 2005-2010	Unused capacity (%) 2010-2015	Unused capacity (%) 2015-2020	Unused capacity (%) 2020-2025
Plant availability factor (%)	64	64	64	64	64
No tax case	0	0	0	0	0
Low tax case	0	0	0	0	0
Moderate tax case	0	0	0	0	0
Reference tax case	0	0	0	0	0
High tax case	0	0	0	0	0

Natural gas based power plants

	Unused capacity (%) 2000-2005	Unused capacity (%) 2005-2010	Unused capacity (%) 2010-2015	Unused capacity (%) 2015-2020	Unused capacity (%) 2020-2025
Plant availability factor (%)	64	64	64	64	64
No tax case	0	0	0	0	0
Low tax case	0	0	0	0	0
Moderate tax case	0	0	0	0	0
Reference tax case	0	0	64	0	0
High tax case	0	0	43.5	0	0

Nuclear power plants

	Unused capacity (%) 2000-2005	Unused capacity (%) 2005-2010	Unused capacity (%) 2010-2015	Unused capacity (%) 2015-2020	Unused capacity (%) 2020-2025
Plant availability factor (%)	75	75	75	75	75
No tax case	75	75	75	75	75
Low tax case	75	75	75	75	75
Moderate tax case	50.96	75	75	75	75
Reference tax case	50.96	75	75	75	75
High tax case	10.87	58.15	75	75	75

For renewable energy based technologies, there is no unused capacity as the model suggests full utilisation of existing capacity in any period in any scenario.

APPENDIX-18

Greenhouse gas emissions in various scenarios (with and without taxes)

Carbon dioxide emissions (thousand tonnes per year)

Base case scenario

	2000-2005	2005-2010	2010-2015	2015-2020	2020-2025
No tax case	276,860	276,981	299,419	344,442	468,603
Low tax case	274,814	276,981	299,419	344,442	468,603
Moderate tax case	274,814	274,870	299,419	344,442	458,677
Reference tax case	81,915	150,219	274,926	344,442	458,677
High tax case	45,823	114,128	238,834	340,882	342,821

Learning technologies scenario

	2000-2005	2005-2010	2010-2015	2015-2020	2020-2025
No tax case	297,866	298,643	299,419	344,442	458,677
Low tax case	297,866	298,643	299,419	344,442	458,677
Moderate tax case	276,860	276,981	299,419	344,442	458,677
Reference tax case	274,814	274,870	277,101	340,882	455,118
High tax case	45,823	114,128	238,834	340,882	410,198

Bound growth scenario

	2000-2005	2005-2010	2010-2015	2015-2020	2020-2025
No tax case	322,307	316,684	323,860	373,938	498,100
Low tax case	321,831	315,590	321,421	344,442	468,603
Moderate tax case	321,831	315,590	321,421	344,442	458,677
Reference tax case	312,670	311,484	289,941	344,442	458,677
High tax case	310,707	311,484	288,723	341,915	343,517

Bound growth with learning technologies scenario

	2000-2005	2005-2010	2010-2015	2015-2020	2020-2025
No tax case	321,831	320,645	321,421	344,442	458,677
Low tax case	321,831	320,645	321,421	344,442	458,677
Moderate tax case	312,670	311,484	312,260	344,442	458,677
Reference tax case	312,670	311,484	289,941	341,915	456,151
High tax case	297,866	298,643	282,967	340,882	410,198

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