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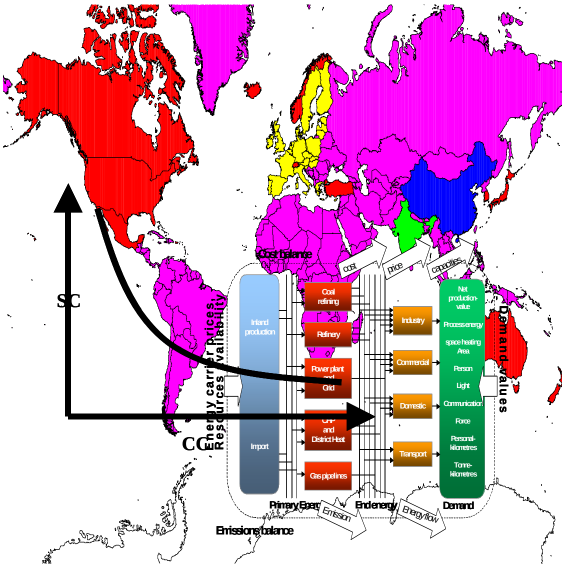
Modelling of Endogenous Technological Learning of Energy Technologies - an Analysis with a Global Multi-regional Energy System Model



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Modelling of Endogenous Technological Learning of Energy Technologies - an Analysis with a Global Multi-regional Energy System Model

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This work is dedicated

to

Sai Baba
and
Dr. Chandrashekhar Mishra

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List of Formulas and Units

Constants and Variables

a	Unit specific cost
b	Learning index
c	Learning index (R&D)
C	Cumulative capacity
CAP	Capacity
CP_FT	Coupling factor
CR&D	Cumulative Research and Development
i	Segment number
INVCOST	Investment cost per unit capacity
key	Key technology
kp	Number of segment
KS	Knowledge stock
LR	Learning rate
MANUF	Manufacturing region
N	Number
NCAP	New capacity
ncap_R&D	New capacity by R&D
NCOST	Non-learning part of the cost
P,Q	Constants
PR	Progress ratio
R&DE	Total R&D expenditure
R&DI	R&D intensity
R^2	Correlation coeficient
TC	Total cumulative cost
TCR	Total cumulative cost by R&D expenditure
TR&DE	Total cumulative R&D expenditure
VAR_INV	Investment variable
WEIG	Weighing factor
X	Time lag between R&D expenditure and knowledge development
α	Y-axis intercept
β	Slope of the segment
δ	Binary variable
δ	Spillover-coefficient
δR	Binary variable for R&D expenditure

λ	Continuous variable
λR	Continuous variable for R&D expenditure

Functions

f(x)	Function of x

Indices

lag	Technology gap
r	Region index
rg	Region group
t,ζ	Time period
te	Technology
v	Vintage

Units

%	Percentage
^{0}C	Degree centigrade
€	Euro
$	Dollar
a	Annum (year)

World regions

EU25	European 25 nations
R_OECD	Rest of OECD
R_NOECD	Rest of Non-OECD
INDIA	India
CHINA	China

Acronyms

AHWR	Advanced Heavy Water Reactor
b/d	Barrel per day
Bts	Billion tonnes
BUs	Billion Units (billion kWhs)
CAP	Capacity
CBM	Coal bed methane
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CEA	Central Electricity Authority
CHP	Combined Heat and Power
CLU	Cluster
CNG	Compressed natural gas
CO_2	Carbon dioxide
DEMO	Demonstration Reactor
DG	Diesel Generator
DOE	Department of energy
ECN	Energy research Centre of the Netherlands
e.g.	For example
EHV	Extra High Voltage
EOR	Enhanced oil recovery
ERIS	Energy Research and Investment Strategy
ETL	Endogenous Technology Learning
ETP	Energy Technology Perspective
EU	European Union
FC	Fictive commodity
FLC	Factor Learning Curve
GAIL	Gas Authority of India Ltd
GDP	Gross Domestic Product
GJ	Gigajoule
GT	Gas Turbine
Gt	Gigaton
GW	Gigawatt
GWh	Gigawatthour
HP	Heat pump
HTH	High Temperature Heat
HVDC	High Voltage Direct Current
IC	Internal Combustion

i.e.	That is to say
IEA	International Energy Agency
IEO	International Energy Outlook
IER	Institute of Energy economics and the Rational use of energy
IGCC	Integrated gasification combined cycle
IIASA	International Institute for Applied Systems Analysis
INV	Investment cost
IPP	Independent power producer
IREDA	Indian Renewable Energy Development Agency
ITER	International Thermonuclear Experimental Reactor
Kg	Kilogram
KPKM	Kilo person kilo-meter
ktce	Kiloton carbon equivalent
ktoe	Kiloton oil equivalent
kWh	Kilowatthour
lbd	Learning by doing
lbu	Learning by using
LNG	Liquefied Natural Gas
LP	Linear programming
LPG	Liquefied Petroleum Gas
LT	Learning technology
LTH	Low Temperature Heat
MANUF	Manufacturing region
MANUF1	Manufacturing region 1
MANUF2	Manufacturing region 2
MARKAL	Market Allocation
Max.	Maximum
MCFC	Molten carbonate fuel cell
MESSAGE	Model for Energy Supply Strategy Alternative and their General Environmental impact
Min.	Minimum
MIP	Mixed integer programming
MMSCMD	Million Metric Standard Cubic Meters per Day
MMT	Million Metric Tonnes
MMTPA	Million Metric Tonnes Per Annum
MNES	Ministry of Non-convention Energy Resources
MOU	Memorandum Of Understanding
Mtce	Million ton of coal equivalent
MTH	Medium Temperature Heat

Mtoe	Million ton of oil equivalent
Mt	Million tonne
MW	Megawatt
MWh	Megawatthour
NCAP_COM	Parameter defined for fictitious commodity in TIMES
NCAP_COST	Cost per unit of new capacity
NGL	Natural gas liquid
OECD	Organisation for Economic Cooperation and Development
ONGC	Oil and Natural Gas Corporation Ltd.
PHWR	Pressurised Heavy Water Reactor
PIL	Petronet India Ltd.
PJ	Petajoule
PKM	Person Kilometer
PLF	Plant Load Factor
POLES	Prospective Outlook on Long-term Energy Systems
PPP	Purchasing Power parity
PSI	Paul Scherrer Institute
R&D	Research and Development
RES	Reference Energy System
RME	Rapsmethylester
SAGE	System for the Analysis of Global Energy markets
SAPIENT	Systems Analysis for Progress and Innovation in Energy Technologies
SAUNER	Sustainability And the Use of Non-rEnewable Resources
SERF	Socio-Economic Research on Fusion energy
SHP	Small hydro Power
SOFC	Solid oxide fuel cell
Solar PV	Solar Photo Voltaic
ST	Steam Turbine
T&D	Transmission and Distribution
tcf	Trillion cubic feet
TCH	Technology
TEEM	Energy Technology Dynamics and Advanced Energy System Modelling
TEG	Key technology
TIMES	The Integrated MARKAL-EFOM System
TKM	Ton Kilometer
TWh	Terawatthour
WDP	Wind Power Density
WEO	World energy outlook

Abstract

The modelling of energy systems, which coevolved from socio-technological interactions and their interplay with the economy, plays a key role in the development of national and international policies to solve the problem of energy poverty. The other important issues addressed by energy system modelling are change in energy infrastructure, paving pathways towards technological sustainability and predicting future energy demand. The clear goal of the analyses is to secure energy supply and to enable the development of fundamental concepts for fulfilling energy demand economically. The main concept behind energy system modelling is to develop energy strategies, while outlining the likely future structure under particular conditions, to gain insights into the technological pathways and policy formulation, to plan expansion of the energy system and to anticipate changes in the market demand. Almost all energy system models are based on optimization of the lowest energy production cost, where the total cost is contributed jointly by the energy carrier's price and the cost of the associated technology subject to technical parameters.

Minimizing the investment cost associated with a given technology is extremely important to sustain the surge in energy demand of the global market. Therefore, how the model applies endogenous investment costs to forecast the future benefit associated with the current knowledge is an important aspect of energy system modelling and analysis. The influence of uncertainty on the learning rates in the endogenization of the learning curve gives impetus to study the diffusion of learning technologies across the regions, as the modelled future return is based on current experience and may lead to uncertainties in the model results. Thus uncertainties in learning rates for technology selection by the model need careful study and analysis. The influence of uncertainties in learning rates on global learning concepts without and with a technology gap is of concern in order to identify the road map of the technologies; and to understand the influence of technology gaps in term of knowledge gaps (higher specific cost) and time lags on the diffusion of learning technology across various regions of the world.

In this modelling study, five regional global models based on TIMES have been developed (TIMES is a model generator and stands for 'The Integrated MARKAL EFOM System'). The regions are defined as 25 European nations (EU25), Rest of OECD (R_OECD), Rest of Non-OECD (R_NOECD), India and China, according to the nations included inside each region and also on their economic categorisation. It is a demand driven, bottom-up and technology abundant model, where GDP, population, and traffic demands are the main drivers for the development of energy demand in the past, present and future. It is a long-term model (1990-2100) consisting of 19 periods with unequal period lengths (5, 8 and 10 years). Each year is divided into three seasons and each season is further divided into day and night, as the smallest time resolution. The entire Reference Energy System (RES) is represented in the Global TIMES G5 model by extraction; inter-regional exchange;

refineries; hydrogen (H_2) production; synthetic fuel production; bio-fuel production; electricity and heat production; Carbon Capture and Storage (CCS); and sector-wise energy demands of industry, commerce, residential and transport, non-energy use and finally an integrated climate module. In the extraction sector, hard coal, lignite, crude oil and natural gas are modelled in four steps with the help of default cost-potential curves. Inter-regional exchanges of ten commodities are modeled for each region inside the TIMES G5 model. The final energy demand of end-use sectors such as industry, commerce and residential are modelled by different end use technologies to satisfy the user's energy demand. Natural and artificial carbon pools are included in the modelling aspect for the abatement of CO_2 or carbon concentrations in the atmosphere to reduce climate warming.

Two climate stabilization scenarios of CO_2 emission of 500-ppmv and 550-ppmv have been used in order to estimate the sectoral restructuring of the energy system across different regions as well as its effect on atmospheric and deep ocean layer temperature rise. The phaseout of polluting fuels and the integration of non-polluting or less polluting fuels and renewable energy sources inside the sectoral energy system predominate across all regions. Sectoral energy demand and total final energy demand decreases in individual regions. Technologies such as fuel cells, fusion technology, Integrated Gasification Combined Cycle (IGCC) with CO_2 sequestration, Combined Cycle Gas Turbine (CCGT) with CO_2 sequestration and hydrogen production with CO_2 sequestration are selected in the stabilization scenarios. The phenomenon of fuel switching starts in the model from 2005 onwards. The CO_2 emission by fossil fuels, by sectors and by regions decreases. Electricity production from CO_2-free energy sources increases. The capacity development increases while the overall utilization factor decreases. The primary energy consumption increases in all regions in the stabilization scenarios. The atmospheric temperature rises by a maximum of $2.41^{o}C$ and the ocean bed temperature rises by a maximum of $0.33^{o}C$ till the year 2100.

The TIMES G5 global model has been developed to test global learning processes for the effect of uncertainties on learning rates of innovative technologies, which depends on the available data base for the technology, i.e., unit specific costs versus cumulative capacity. The study shows how the spreading of climate compatible and developing technologies inside the energy system depends on the uncertainty of learning rates or progress ratios. The study also reflects how uncertainties in the learning rates affect the technology diffusion inside regional energy systems. In order to reflect the technology integration subject to the influence of uncertainties on the progress ratio, a minimum cost approach has been developed and applied. The global learning process considering technology gap methodologies has been developed and tested in this work for three different progress ratios of each technology; representing the uncertainty of the technological return. The technology gap is tested, where it is represented by a higher specific cost of the technology for developing regions and a lower specific cost for developed regions, assuming that they use the same product produced in the manufacturing region in the same time period. In another approach, the technology gap is represented by a time lag in capacity transfer, i.e., knowledge spillover, because capacity is the proxy for knowledge in learning theory. The specific cost of new technologies differs across the regions in both types of technology gap approaches, in relation to the variation of the discount rate, technology gap by period and duration in years of the period.

This study shows the penetration and integration of new technologies such as IGCC, CCGT, solar photovoltaic, wind onshore, wind offshore and geothermal heat pumps inside the energy system of different regions. Variation of results observed by the inclusion of global learning without and with technology gaps in the form of higher specific cost (knowledge gap) and time lag. IGCC technology reaches its maximum potential in all scenarios across the globe. IGCC technology is preferred in the case of global learning without knowledge gap and time lag across developing regions compared to global learning with knowledge gap. CCGT technology development in manufacturing region decreases in global learning with technology knowledge gap compared to without knowledge gap concept. Wind onshore penetrates more in EU25 and R_OECD regions and in the energy systems in a global learning concept without knowledge gap. Developed regions use more learning technology in the global learning with time lag concept because of the advantage of early investment cost reduction of learning technologies contributed by developing regions. Geothermal Heat Pump (geothermal HP) penetrates more across all regions and in all scenarios as the technology is modeled for global learning without knowledge gap and time lag. Bio-gasification, solid oxide fuel cells and molten carbonate fuel cells do not enter into any energy system under any scenario. It is observed that learning technology diffuses more in higher learning rates and less in lower learning rates across the regions and the globe. The development of specific costs of innovative technologies is observed differently by period for developing and developed regions in global learning with technology gap in the form of higher specific cost approach. Furthermore the study has successfully implemented the minimum (floor) cost approach inside global learning within the energy system models.

Kurzfassung

Die Modellierung von Energiesystemen entwickelte sich in Wechselbeziehung mit sozio-ökonomischen und technologischen Fragestellungen. Sie spielt eine Schlüsselrolle in der Entwicklung nationaler und internationaler Politik und dient dazu, Probleme wie Energieknappheit zu lösen, Möglichkeiten zur Änderung von Infrastrukturen im Energiesektor aufzuzeigen, den Weg für eine technologische Nachhaltigkeit zu ebnen und den zukünftigen Energiebedarf zu prognostizieren. Diese Analysen haben als ein wesentliches Ziel, die Energieversorgung der Wirtschaft zu sichern, und die Entwicklung grundlegender Konzepte hierfür zu ermöglichen. Insbesondere die Langzeitmodellierung von Energiesystemen ist hierbei eine interessante und spannende Aufgabe. Das Hauptkonzept der Modellierung ist die Entwicklung von energiewirtschaftlichen Strategien, das Abbilden von wahrscheinlichen Zukunftssituationen unter bestimmten Voraussetzungen, die Analyse von technologischen, strukturellen und politischen Entwicklungen, das Planen von Erweiterungen der Energiesysteme und – analog zum privaten Sektor – das Vorhersagen von Energiebedarf und Marktstrukturen. Fast alle Energiesystemmodelle basieren auf der Optimierung der Kosten der Energieerzeugung, welche die Kosten für Energieträger und Technologien zur Energiebereitstellung unter Berücksichtigung verschiedener technologisch-ökonomischer Parameter beinhalten. Die Technologien der Energieerzeugung stellen hierbei das Basisinstrument der Energieversorgung und die Hauptkomponente sowohl für die Energiekosten als auch die wirtschaftliche Entwicklung dar.

Die Reduktion der Investitionskosten für Anlagen zur Energieerzeugung ist eine wesentliche Fragestellung. Hierbei ist von großer Bedeutung, wie das Energiesystemmodell endogen Investitionskosten einsetzen kann, um zukünftige Potenziale ausgehend von den derzeitigen Kenntnissen zu prognostizieren. Der Einfluss der Unsicherheit von Lernraten bei der Endogenisierung des Lernprozesses muss untersucht werden, da die modellierten zukünftigen ökonomischen Parameter durch die heutigen Erfahrungswerte bedingt sind und dies zu unsicheren Modellergebnissen führen kann. Deshalb müssen insbesondere die Unsicherheiten der Lernraten für die Technologieauswahl sorgfältig untersucht werden und Fehler bei der Vorhersage der zukünftigen Technologieentwicklung analysiert und korrigiert werden. Der Einfluss der Lernraten-Unsicherheiten ist in einem globalen Lernkonzept unter Berücksichtigung von sogenannten Technologielücken von Interesse, um die Entwicklung und Implementierung von neuen Technologien zu untersuchen. Dadurch kann der Einfluss von Technologielücken, d.h. von zeitlichen Verzögerungen zwischen Verfügbarkeit und Implementierung von Technologien, in Form von höheren spezifischen Kosten und einer verzögerten Marktdurchdringung in verschiedenen Regionen des TIMES G5-Modells dargestellt werden.

Im Rahmen dieser Studie wurde ein fünf Regionen Modell auf Basis des TIMES (The Integrated Markal Efom System) Modell Generators entwickelt. Die Regionen sind definiert als die 25 europäischen Staaten (EU25), die restlichen Länder der OECD, die restlichen Länder außerhalb der OECD, Indien und China. Das Modell ist gesteuert durch den Energiebedarf, verwendet einen „Bottom-up"-Ansatz und beinhaltet die unterschiedlichsten Technologien. GDP, Bevölkerung und Verkehrsleistung sind die wesentlichen Faktoren für die Entwicklung des Energiebedarfs in der Vergangenheit, der Gegenwart und der Zukunft. Bei dem Modell handelt es sich um ein Langzeitmodell (Zeitraum 1990 bis 2100), das aus 19 Zeitperioden mit unterschiedlichen Längen (5, 8 und 10 Jahre) besteht. Jedes Jahr ist in drei Abschnitte unterteilt und jeder Abschnitt in Tag und Nacht als der höchsten zeitlichen Auflösung. Das gesamte Referenzenergiesystem (RES) ist im globalen TIMES G5 Modell abgebildet durch die Energieträgergewinnung, den überregionalen Markt, Raffinerien, die Produktion von Synthesekraftstoffen, Biokraftstoffen, Wasserstoff, Strom und Wärme, Technologien zur CO_2-Abscheidung und -Speicherung, den sektoralen Energiebedarf von Industrie, Gewerbe, Haushalten und Verkehr, den stofflichen Einsatz von fossilen Energieträgern und schließlich durch ein integriertes Klimamodul. Die Gewinnung der Energieträger Steinkohle, Braunkohle, Rohöl und Erdgas wird in vier Schritten mit Default-Kostenpotenzialkurven modelliert. Für jede Region wird der überregionale Handel von zehn Gütern innerhalb des TIMES G5-Modells abgebildet. Der Endenergiebedarf von Sektoren wie der Industrie, dem Gewerbe und den Haushalten wird mit unterschiedlichen Endnutzertechnologien modelliert. Natürliche und anthropogene Methoden der CO_2-Abscheidung und -Speicherung werden als CO_2-Senken und Maßnahmen zur Minderung der Klimaerwärmung berücksichtigt.

Im Rahmen der Arbeit wurden zwei Szenarien zur Stabilisierung der CO_2-Emissionen auf einem Niveau von 500 ppmv und 550 ppmv betrachtet, um die sektorale Restrukturierung des Energiesystems in verschiedenen Regionen sowie den Temperaturanstieg in der Atmosphäre und am Meeresgrund abzuschätzen. In allen Regionen des sektoralen Energiesystems geht die Nutzung klimaschädlicher Energieträger zurück. Stattdessen dominiert die Nutzung nicht- oder weniger klimaschädlicher Energieträger sowie die Verwendung erneuerbarer Energiequellen. Der sektorale Energiebedarf und der totale Endenergiebedarf der einzelnen Regionen verringern sich. Technologien wie Brennstoffzellen, Fusionstechnologie, kombinierte Gas und Dampf Prozesse mit CO_2-Abscheidung (mit integrierter Kohlevergasung (IGCC) oder mit Gasturbine (CCGT)) und Wasserstoffproduktion mit CO_2-Abscheidung werden in den Stabilisierungsszenarien eingesetzt. Der Wechsel bei den Energieträgern beginnt im Modell ab dem Jahr 2005. Die CO_2-Emissionen je Brennstoff, Sektor und Region verringern sich, die Stromproduktion mit CO_2-freien Energieträgern steigt. Die Anlagenkapazitäten nehmen zu, während die Nutzungsgrade sinken. Der Primärenergieverbrauch erhöht sich bei den

Stabilisierungsszenarien in allen Regionen. Die Temperatur der Atmosphäre steigt bis zum Jahr 2100 um maximal 2.41°C an, die Temperatur am Meeresboden um maximal 0.33°C.

Das globale Modell wurde entwickelt, um die globalen Lernprozesse im Hinblick auf die Unsicherheit der Lernrate von innovativen Technologien untersuchen zu können. Diese hängen von der Qualität der verfügbaren Datenbasis zur Abbildung der Technologien ab, wie spezifische Kosten und Gesamtkapazitäten. Die Studie stellt dar, wie klimaverträgliche und sich entwickelnde Technologien in Abhängigkeit von der Unsicherheit der Lernrate bzw. Fortschrittsrate Eingang in Energiesysteme finden. Die Studie zeigt auch, wie die Unsicherheit der Lernrate die Auswahl von Technologien bestimmt. Um die Größe der möglichen Bandbreite der Modellergebnisse zu begrenzen, wurde ein Ansatz basierend auf Mindestkosten entwickelt und angewendet. Die globalen Lernprozesse unter Berücksichtigung von Technologielücken wurden in dieser Arbeit mit drei unterschiedlichen Fortschrittsraten je Technologie untersucht, welche die Unsicherheiten der technologischen Entwicklung in Bezug auf Implementierung und Kosten darstellen. Es wurde untersucht, inwiefern Technologielücken bei vergleichbaren Prozessen und Zeitperioden sich als höhere spezifische Kosten der Technologien in Entwicklungsländern und niedrigere spezifische Kosten in entwickelten Regionen widerspiegeln. In einem weiteren Ansatz wurden die Technologielücken als zeitlich verzögerte Kapazitätsentwicklungen abgebildet, da in der Lerntheorie die Kapazität der Fortschritts-Indikator ist. Die spezifischen Kosten neuer Technologien in den Regionen unterscheiden sich bei beiden gewählten Ansätzen zur Modellierung von Technologielücken in Abhängigkeit von Diskontraten, Technologielücken je Periode und der Länge der untersuchten Zeitperioden.

Im Ergebnis stellt die Arbeit die Marktdurchdringung und Integration von neuen Technologien wie IGCC, CCGT, Photovoltaikanlagen, „Onshore“- und „Offshore“-Windkraftanlagen und geothermischen Wärmepumpen in den Energiesystemen verschiedener Regionen dar. Unterschieden wird dabei zwischen der Anwendung eines globalen Lernkonzeptes mit und ohne Berücksichtigung von Technologielücken, die in Form von höheren spezifischen Kosten der Technologien (knowledge gap) und einer zeitlichen Verschiebung ihrer Verfügbarkeit (time gap) abgebildet werden. IGCC Technologien erreichen in allen Szenarien ihr maximales Potenzial. Sie werden in sich entwickelnden Regionen bevorzugt bei Anwendung des globalen Lernkonzepts ohne knowledge gap und ohne time gap eingesetzt. Die Entwicklung der CCGT-Technologie in produzierenden Regionen verlangsamt sich beim globalen Lernkonzept mit knowledge gap gegenüber dem Konzept ohne knowledge gap. Die Marktdurchdringung von Onshore Windkraft Anlagen findet vor allem in den Regionen EU25 und R_OECD und bei Anwendung des Lernkonzepts ohne knowledge gap statt. Entwickelte Regionen setzen Lerntechnologien insbesondere beim Lernkonzept mit time gap ein wegen des Vorteils der frühen Investitionskostenreduzierung von Lerntechnologien aus sich entwickelnden Regionen. Geothermische Wärmepumpen werden in allen Regionen und Szenarien bevorzugt eingesetzt, da diese Technologie mit dem globalen Lernkonzept ohne knowledge gap und ohne time gap modelliert wurden. Biomassevergasung, Festoxid-Brennstoffzellen und Schmelz-Karbonat-Brennstoffzellen finden in keinem der Szenarien Eingang in eines der Energiesysteme. Weiter wurde beobachtet, dass das Spektrum der eingesetzten Lerntechnologien bei Annahme hoher Lernraten größer ist als bei niedrigen Lernraten. Die Entwicklung der spezifischen Kosten für innovative Technologien verläuft in Abhängigkeit vom globalen Lernkonzept, den betrachteten Technologielücken und den resultierenden verschiedenen spezifischen Technologiekosten in Entwicklungsländern und entwickelten Ländern unterschiedlich. Des weiteren konnte die Studie erfolgreich einen Modellansatz basierend auf Mindestkosten in den globalen Lernprozess des Energiesystemmodells anwenden.

1 Introduction

1.1 Background and motivation

Energy system modelling, a valuable tool for energy system analysis, has been coevolved from socio-technology interaction in terms of technology dissemination. Interaction of system modelling and analysis with the economy plays a key role in the elaboration of national and international strategies towards policy formulation, combats the threat of climate change, solves the problem of energy poverty, and makes changes in energy structure, extension and expansion. The above mentioned factors reflect the pathways towards the technology sustainability especially concerning the long-term models. Long term modelling of energy economic model is always developed for the multifaceted scenarios analysis in which the climate problem is the main concern. A minimum time period of 100 years is necessary because of the Greenhouse Gas (GHG) effect, which changes the climate over a period of 50 to 100 years or more. Also the long-term model reflects the sustainability of the resources and reserves of a region; and the trade dependencies of the region on energy carriers. In the long-term global energy model, technological dynamics is generated by diffusion of new technologies comprising technology adoptability, consumer attitude to cost levels, performance index and safety concerns. Regarding the evolution of the global energy systems, technology plays a fundamental role in their cost structure, environmental impacts, flexibility and available policy alternatives /Rogner, 1996a, IPCC, 2000/. Shaping of technological trajectories to a large extent depends on environmental impacts, resource availability, efficiency, specific cost, technical skill, market demand and future sustainability.

Technology is the fundamental block, key component and essential element of energy system models, which does not coevolve autonomously but rather by endogenous socio-economic interaction /Barreto 2001/. Almost all energy system models are based on optimization of total cost, in which the technology constitutes the main factor, especially its investment cost, out of all techno-economic parameters. The reduction of cost associated with the technology in any form and its dissemination into future energy systems are two important spheres that need special focus at all times /Barreto 2001/. The dissemination of technology in future energy markets plays an important role in the elaboration of national and international policies. Recent growing concern on environmental and climate change requires the understanding of future technological dynamics and its penetration across world regions especially of zero-emission, climate friendly and low-emission technologies.

The main analytical approach towards the cost reduction of a technology is based on the learning theory approach, which states that the specific investment cost of any technology reduces with respect to knowledge accumulation through the deployment of capacity and R&D expenditure /Blesl et al. 2005/. The indigenization of the learning approach inside energy optimization models has many advantages compared to exogenous models in terms of consistency and decision making and provides qualitatively new insights about the penetration of technologies inside the future energy system.

The dynamics of future technological pathways subject to a multi-regional concept require consideration of knowledge spillover from one region to another and its behaviour with respect to time and technology gaps. The global free trade market and economic globalisation dramatically increase the transboundary flows of people, goods and information; these constitute the basic parameters of global technology spillover /Watanabe et al. 2000/ and technological learning in-between the forerunner and entrant countries can be mapped to global learning by learning spillover /Schaeffer et al. 2004/. Learning processes are considered global rather than regional from the perspective of innovation diffusion and technological spillover through the product dissemination, import and export of product through licensed agreements, technology transfer by the Clean Development Mechanism (CDM) and Joint Implementation (JI) under the Kyoto Protocol, where it states that deployment of capacity in some region of world contributes to the learning process in other regions /OECD/IEA 2000/. From these points, it can be concluded that the development of technology which takes place in one region diffuses to other region in the same period or after a certain time gap /Gielen et al. 2004/. On the other hand, if all regions use the same technology in the same time period, then they see different investment costs per unit capacity of the technology.

Integration of a technology in the global market and its dissemination in one corner of world, when germinated in another, is described as learning spillover in global learning. The transfer rate of the product is facilitated by the speed of knowledge transfer and diminution of the communication gap (transportation system). Some technologies, which are truly global (electricity and steel production plants) are available rapidly in the global market and benefit by their utilisation worldwide /Loulou et al. 2005/. Thus international co-operation is required for new, efficient and climate compatible technologies, which are expensive but still promising technologies for future global learning /Barreto 2001/. Developing and third world countries have no basis to learn on new, climate friendly and low-carbon technologies, as there is no manufacturer and poor market development; it also requires a huge amount of learning investment and above all requires sound knowledge about technology.

It is important to realize and develop a methodological approach to create a technological road map towards future technological regimes on global energy circumstances and to accelerate climate beneficial technologies in the future energy mix. Also, it is relevant to know how the methodological approach contributes to global learning through the technology gap to the sustainability of global energy issues and achieves the technology path in a long-term goal. It is quite interesting to understand, handle and perceive global learning by endogenisation inside the multi-regional global energy model. This approach to the multi-regional energy system reflects the advantages drawn by regions that lack technology from host regions in the form of the dissemination of technology, technological knowledge transfer, learning investment and rate to promote the production of nascent technologies.

Progress ratio represents the development of specific cost reduction of a technology by a certain percentage with respect to doubling of cumulative capacity. The calculation of progress ratio depends on the state of the technology (invention, innovation and maturation) at the point that the data has been collected. Generally the innovation and invention states are rapid change zones, where the technology changes its specific cost very fast. Thus calculation of the progress ratio and learning rate at certain stage is highly associated with uncertainty that is reflected in technology diffusion inside the energy system models.

Technological learning on a regional basis is difficult to handle in multi-regional energy system models due to the uncertainty and inconsistency associated with progress ratios or learning rates. It is difficult to get accurate values of the learning rates or progress ratios on a local and regional basis, as it is not certain from which region the development of the technology comes. Thus there is a lot of uncertainty associated with the learning rate of a specific technology in a regional learning concept.

1.2 Objectives

It is necessary to realize and develop the methodological approach to pave the technological road map towards future technological regimes on global energy circumstances and acceleration of climate beneficial technologies in the future energy mix by taking consideration of exogenous and endogenous global learning. It is also relevant to know how the methodological approach on global learning spillover contributes to the sustainability of global energy issues and achieves the technology pathway as a long-term goal. It is of interesting to understand, handle and perceive global learning by endogenisation inside the multi-regional global energy model without and with time lag and knowledge gaps, which are the key factors of the technology gap. It is highly relevant to understand the behaviour of the learning technologies inside the regional energy system in the context of global learning subject to uncertainty in learning rates of the learning technologies in the global context. It is interesting to know the behaviour of the energy system of each region subject to the resource availability in order to understand the effect of energy structure, consumption, technology utilization, import and export on sustainability of the regions on energy infrastructure. It concerns to study the regions of energy system of flourishing economies and high population development. Moreover it is interesting to know the behaviour of the regional energy system for the allocation of the sectoral energy in the climate stabilization cases, i.e., in which sector the energy structure changes and how the development takes place.

The objective of this thesis is the development of five regional global energy model TIMES G5 and testing of different type of learning methodologies subject to uncertainty in learning rates. The methodological approaches are based on global learning without knowledge gap and time lag on the diffusion of the learning technologies across the regions inside the TIMES G5 model with uncertainty of the learning rates. The other approach includes global learning subject to knowledge gap in which the developing regions see higher specific costs of the learning technology for the knowledge gap and the developed regions do not see the higher specific cost of the learning technologies produced in the manufacturing region. The global learning with knowledge gap is tested as well with the uncertainty in the learning rates of learning technologies. In addition the global learning with time lag and knowledge gap are tested on the medium progress ratio for comparison of the two approaches.

The purpose of this study is to understand and realize the effect of uncertainty of learning rates on technology diffusion across different regions of world in the TIMES G5 model. The uncertainty of learning rates is tested in global learning without knowledge gap and time lag approaches. Also the knowledge gap and time lag approaches have been tested on global learning concept with uncertainty of learning rates. The approach on global learning system reflects the advantages drawn by regions lacking technology from host regions in the form of dissemination of technology, technological knowledge transfer, learning investment and rate to promote the production of nascent technologies in global context. Not only developing regions always benefited in the global learning scenarios but also the developed regions gain advantage from global learning in the early reduction of investment cost of learning technologies contributed by developing regions. Also the aim of this study is to realize subsequent sustainability of the energy system, behaviour of technological dynamics and a future road map of learning technologies for the fulfilment of the energy demand on long-term goal. The scenarios on stabilization of atmospheric carbon concentrations have been developed and tested to investigate the behaviour of the energy system subject to climate stabilization.

1.3 Structure

Chapter 1 contains an introduction, the objective of the dissertation and the structure of the thesis. The energy situation of the world, India and China with their present prospects on the state of energy infrastructure and circumstances is described in Chapter 2. This chapter also contains the GHG emissions, especially CO_2 and the challenges associated with the energy system of aforementioned regions.

Chapter 3 delivers the state of the art on the learning phenomenon of global learning, focussing on the technology gap or knowledge gap in terms of higher specific cost and time lag concepts. This chapter articulates the theoretical and mathematical equations of each approach on global learning in a multi-regional framework. Comparison of strengths and weaknesses by different approaches are made and the uncertainty associated with learning rates is important in this chapter. In addition, the fundamental concept and evaluation of global learning is presented in this chapter. This chapter contains the knowledge lack or technology gap approach by higher specific cost of technologies in regions that lack knowledge and time lag in technology transfer inside those regions.

Chapter 4 describes the TIMES G5 global model, the philosophy behind its development, the reference energy system upon which it is supported. It describes the basis of assumptions on which the energy demand is projected, i.e., the drivers of the energy demand. It contains the development of the key indicators for each sector and each type of useful energy demand. Results of base case, climate stabilisation scenarios, global learning scenarios without and with time lag, global learning scenarios without and with knowledge gap are presented in Chapter 5. Chapter 6 contains the conclusion and recommendations. References used for this study are presented at last.

2 Energy Situation and GHG Overview

Energy is a prerequisite, essential, critical and fundamental factor for socio-economic development of a nation. Global experience proves that energy is a basic input for all economic activities, human development and need to keep pace with growth of economy /PETROFED/. The economic growth has impact on per capital consumption of energy, which is the yardstick for the measurement of the economy of a country that also reflects the standard of living of the inhabitants. It is therefore the responsibility and prime importance of energy industry to satisfy the consumer's energy demand, which is the basic need for all activities. That is why energy industry is extremely important all around the world containing a large number of peripherals within it. Hence uninterrupted and reliable energy supply is a challenge not only for the present time but also for the future. The energy supply should satisfy the demand by practicability, affordability, while being environmentally sustainable and safe. As a result of a large amount of money is being spent in research and development activities in order to support the increase in future energy demand in an environmental sustainable manner. Affordable energy supply and efficient energy use are indispensable ingredients of energy infrastructure of a nation and represents its well-being. To achieve this all regions around the globe are putting various measures in place to achieve the goal. In essence, gaining and protecting access to foreign energy resources was main reasons of major conflicts around the world during twentieth century and may continue in twenty first century also /DOE (SERD) 1995/. This chapter elaborates the GDP, population, energy consumption by end use sectors, electricity production, energy from renewable and CO_2 emission of the world, India and China, their past and present condition on the energy situation.

2.1 World energy situation

The GDP of world attained 28276, 31897 and 38336 trillion €(00) respectively in the years 1990, 1995 and 2000. Likewise the population of world was 5228 million in year 1990, 5631 in year 1995 and 6061 in year 2000 /WEO 2004/. In total GDP, developed region has major share compared to developing region and the reverse phenomenon is observed in case of world population.

Primary energy consumption of world was 8.3 Gtoe in 1990 /Ito et al. 2000/. The IPCC study of AIM model represents the world primary energy consumption as 8.973 Gtoe in year 1990 and 10.191 Gtoe in year 2000 /IPCC 2000/. The study of ASF model of IPCC presents the world primary consumption as 7.609 Gtoe in year 1990 and 9.079 Gtoe in year 2000 /IPCC 2000/. World primary energy demand is increased from 5536 Mtoe in 1971, to 7845 Mtoe in 1991, to 8743 in 1997 and to 9179 Mtoe in 2000 /WEO 1994, 1995, 2000, 2002, 2004/. In total energy demand, share of exhaustible fossil energy is around 80% and rest is coming from nuclear and renewable. In fossil fuels, oil holds greatest share (around 36%) followed by coal (around 23%) and natural gas (around 21%); nuclear hold its share around 7% in total energy demand and renewable around 13%, in which traditional biomass is included and it bears greatest share among all other renewable sources (see Figure 2-1 and Figure 2-2). The traditional biomass is the fuel for poor in the developing regions and utilised mainly in the household sector. The primary energy demand by EU25 was around 1.447 Gtoe in year 1990 and 1.622 Gtoe in year 2000. Similary in year 1990 and 2000, the total primary energy demand by R_OECD, R_NOECD, India and China was respectively around 3.117 Gtoe, 2.987 Gtoe, 0.352 Gtoe, 0.831 Gtoe and 3.677 Gtoe; 3.13 Gtoe; 0.5 Gtoe; 1.161 Gtoe. Oil holds a major share in the primary energy demand of EU25, R_OECD and R_NOECD regions, whereas coal in India and China energy system. Coal holds second largest share in primary energy consumption followed by natural gas in primary energy consumption of EU25 and R_OECD regions, whereas natural gas is in second position and coal is in the third place for R_NOECD region. In case of India and China, oil holds the second largest share and natural gas places in third position.

The final energy demand of globe was 4200 Mtoe in 1971, 5537 Mtoe in 1991 and 6032 Mtoe in 2000 (see Figure 2-1). In final energy consumption, oil maintains its highest share followed by natural gas, renewables, electricity, coal and heat. Generally the polluting energy carriers are phased out slowly and the commercial fuels fulfil the gap. In the industrial sector of world, total final energy demand was approximately 1798 Mtoe in year 1990 and 2183 Mtoe in year 2000. The energy demand by commerce sector was 788 Mtoe in year 1990 and 900 Mtoe in year 2000. The residencial sector energy demand of world was 935 Mtoe in year 1990 and 1117 Mtoe in year 2000 /WEO 2004/ as shown in Figure 2-2. The non-energy use demand of whole world was 232 Mtoe in year 1990 and 221 Mtoe in year 2000 /WEO 2004/. The sectoral energy demand increases rapidly for industry, commerce and transport sectors, but the non-energy use sector decreases the demand marginally. Transport sector consumes more oil and less other fuels. The total energy demand in world transport sector was 856 Mtoe in 1971, 1646 Mtoe in 1997 and 1775 Mtoe in 2000. More than 95% of the fuel consumption is oil and rest is from other energy carriers /WEO 2004/.

Production of electricity of world depends heavily on the fossil fuels and accounted around 64% in total (see Figure 2-2). Corresponding to this, also the development of the capacity occurs. The global electricity production attained the value of 5217 TWh in 1971, 13949 TWh in 1997, 15391 TWh in 2000 and 16074 TWh in 2002 /WEO 2004/. The electricity production will maintain its increase in trend for the increase in demand of electricity in developing regions. The increase in standard of living increases the per capita electricity demand. The world average electricity demand per capita was around 4700 TWh in 1990, 5100 TWh in 1995, 5600 TWh in 2000 /WEO 2004/. The electricity generation capacity of world energy system increases day by day and also the trend will continue in future. Likewise the capacity development of the global electricity production sector reached 3221 GW in 1997, 3397 in 1999 and 3719 GW in 2002. The capacity of renewable increased from 57 GW in 1999 to 77 GW in 2002 /WEO 2004/ and the electricity produced from renewable hiked from 249 TWh in 2000 to 317 TWh in 2002 /WEO 2004/. The demand of electricity increases for the developed regions in these periods for their high GDP growth and high standard of living.

The global atmospheric carbon dioxide concentration increase from the pre industrial level of 280 ppmv to 365 ppmv at present /climnet.ctap/ and may follow the increase in trend for future, in which the major contributors are power production, transport and industry sectors. The world CO_2 emission reached 21579 Mt in 1991 /WEO 1994/; 22639 Mt in 2000 /WEO 2002/; and 23579 Mt in 2002 /WEO 2004/. The /WEO 2004/ projects the total world CO_2 to reach the figure of 38214 Mt in 2030, whereas /IEO 2004/ projects the value of 37124 Mt in year 2025. Results of the Business As Usual (BAU) case for the year 1990, 2050 and 2100 indicate that world CO_2 emission strikes the value 21633, 48766 and 58300 Mt CO_2 /Ito et al. 2000/, CO_2 emission was about 21176 Mt CO_2 1990 /WEO 1995/. The global CO_2 emission rise from 6.1 billion tons of which India has share around 3% in 1990 /Sukla and Rana/.

The energy demand for developed regions hold a big share in total primary, final and sectoral energy demand. The developing regions are tending their rise in energy demand in different sectoral energy demand. Share of commercial fuel is in higher side for developing regions compared to traditional fuel and the share of traditional fuel holds a greater share in developing regions compared to commercial fuels. The increases in share of commercial fuel take place in the end use sector of all regions with respect to time. From emission point of view, developed regions hold greater share but compared to per unit final energy or unit primary energy consumption, developing regions hold a big share as they are using more polluting and obsolete technologies for the energy conversion.

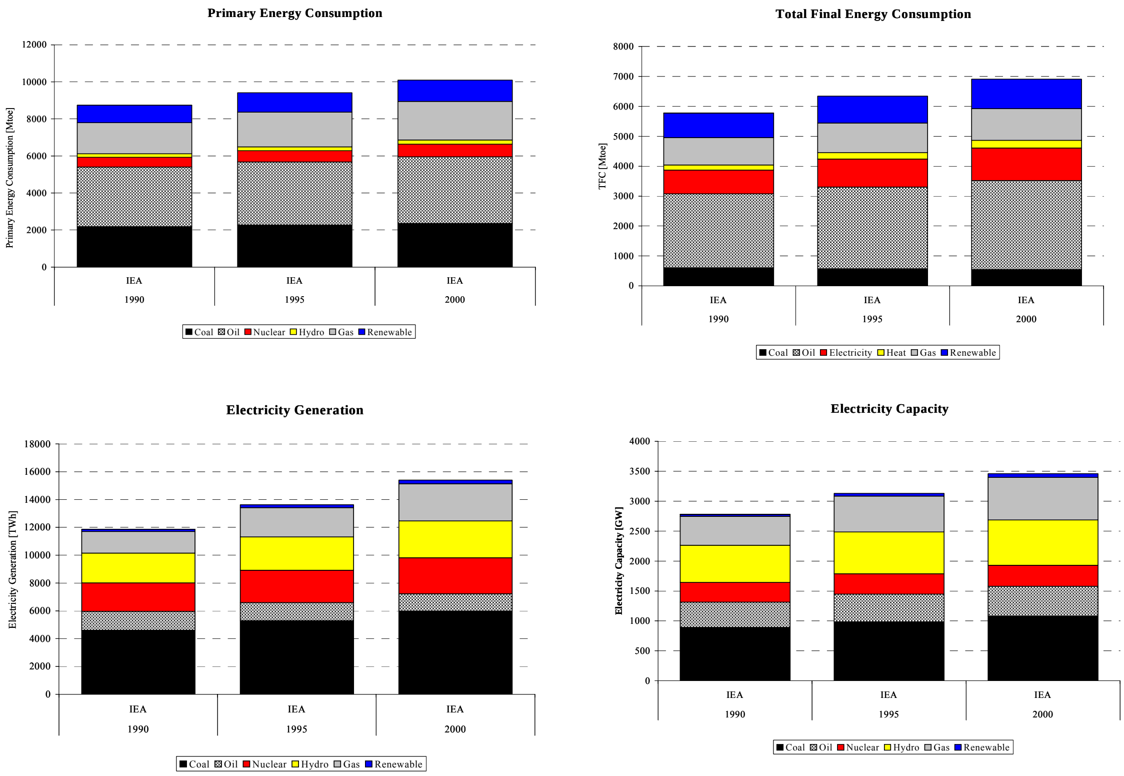

Figure 2-1: World primary and final energy consumption, electricity generation and capacity by fuels (1990 to 2000)

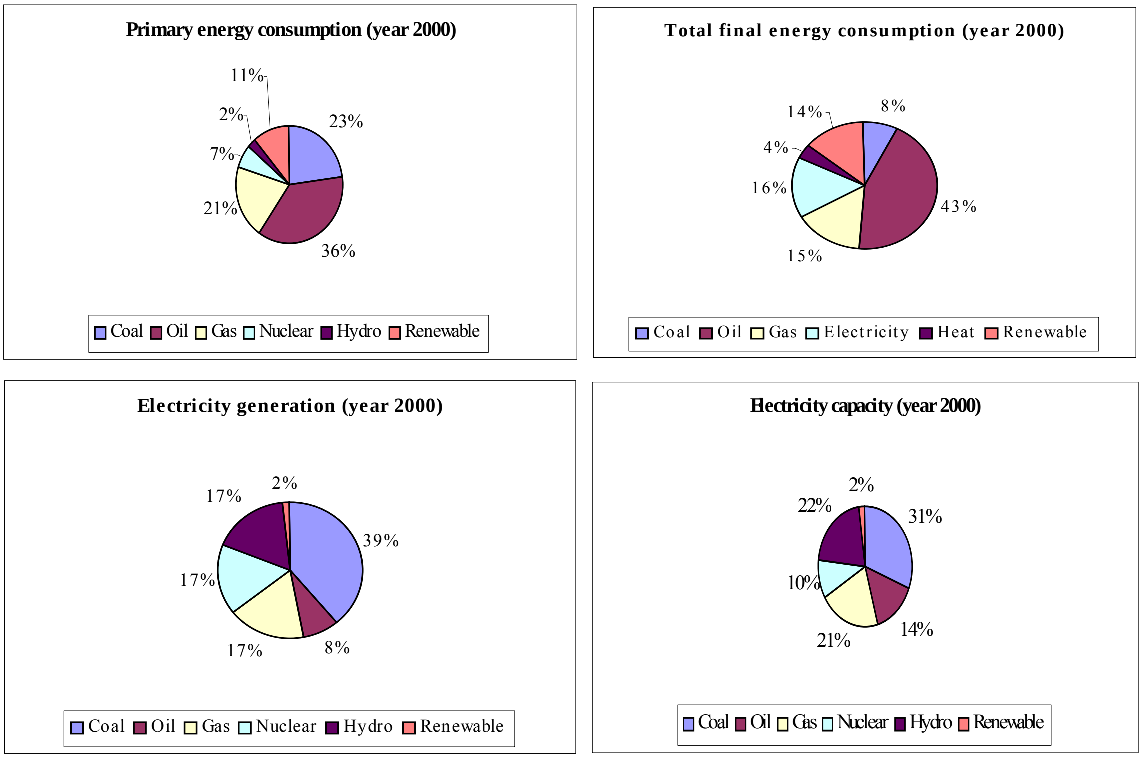

Figure 2-2: World primary and final energy consumption, electricity generation and capacity in the year 2000

2.2 Energy situation of India

It incites to know the energy situation of India at present and also its future structure as the region is passing through the blooming economy and also from resource side the region is poor in clean and efficient fuels. Therefore this region gains attention to study on its energy situation and GHG emissions.

2.2.1 General overview, GDP and population

India is a large country spread over an geographical area of 3.29 million square kilometer (329 hectares), which is slightly more than one third of the United States /indianembassy/. India is the world's fourth largest economy in terms of Purchasing Power Parity (PPP) and fast growing economy at present. The GDP in terms of PPP was approximately 2.836 trillion €(00) in year 2003 /indiaonestop/. During last four years the growth of GDP remained on an average of 7%. It is projected that the real GDP growth rate of India will remain around 6% for next several years /Sukla et al. 2001/, but IEA has projected the GDP growth rate as 4-6% from 2000 to 2030. During independence (1947), population of India was around 300 million in comparison to 846 million in 1991 census and 1028 million in 2001 census /India.census/, and secured second position after China. The population growth rate remained on an average of 1.7%/a for last decade and may continue at the rate of 1.4%/a in future. India has implemented the population growth control policy, but policy measure has not been enforced stringently and worked effectively.

2.2.2 Energy consumption

The incremental energy demand is high in the world, incited by higher GDP and population growth rate and increase in standard of life. India has equally empower with exhaustibel and renewable resources and exploited for the utilisation of the resources well in balance. Biomass, coal, oil and natural gas are main resource of primary energy. Out of these, biomass, the non-commercial energy prevails all others. Within commercial energy, coal takes the leading role followed by oil and natural gas. In India, biomass is basically the fuel for household sector in rural areas because around 70-80% of the total population reside in the rural area and that to 35-40% of the population are below poverty line and it is not feasible on their part to afford commercial energy. The pattern of supply and consumption of energy has changed over the past several years such that commercial primary energy demand has increased from 177 Mtoe in the year 1990 to 293 Mtoe in the year 2000 and its share within total has increased from 50% in 1990 to 60% in 2000 /WEO 2004/. India is a net importer of energy as the production of primary energy is always less than consumption. Energy consumption by India is about three percent of the world's total energy and sixth largest energy consumer /cslforum.org/.

Total final energy demand of India in past and at present by IEA is different in different years. Total final energy consumption was around 285 Mtoe in 1990, 335 Mtoe in 1995 and 355 in year 2000 /WEO 2004/. In total final energy consumption electricity, oil, natural gas and renewable increase their shares from 1990 to 2000, whereas coal reduces its share. The demand of final energy by all sectors increases but the high growth rate occurs in residence and transport sector. The high GDP growth rate and increase in standard of living drags for more energy demand at present and may continue in future. Shifting of less polluting fuels from heavy polluting fuel takes place with passage of time. The energy consumption per GDP remains in higher side compared to world and energy consumption per capita remains in lower side of world average. At present the GDP and population growth rate is in higher side compared to world average.

2.2.3 Electricity production sector

The power sector is the main sector of energy production. Electricity generation expansion is growing at a prodigious rate and doubled since 1990. The generation in the country has increased from 301 TWh during 1992-1993 to 531.6 TWh during 2002-2003, and 558 TWh by the year 2003-2004. Currently India is the seventh-greatest electricity-consuming country (accounts about 3.5% of total electricity consumption of world) /DOE.india/. During early fifties the per capita electricity consumption was 15 kWh compared to 334.24 kWh during 1996-97 and 348.50 kWh during 1997-98. At present the average electricity consumption per capita is around 545 kWh compared to world average of around 2370 kWh. Load shading, brownouts and blackouts are the common phenomenon in many parts of India due to inadequate supply that is unable to meet the demand during off-peak and peak periods. Overall electrification rate has been reached 80% in the country and about 85% of the villages have been electrified except far-flung areas in North Eastern states, where it is difficult to extend the grid supply.

India is currently secured sixth position in terms of total installed electricity generating capacity in the world and accounts for about 3.3% of world total. Total utility capacity was 1713 MW during 1950 and increased more that 65 folds to present position /teriin.pradeep/. Total installed capacity of electric power generating stations under utilities was 107.9 GW as on 2003 consisting of 76.6 GW thermal, 26.9 GW hydro, 27.2 GW nuclear and 1.73 GW wind, which has increased to 112.05 GW as on 2004 consisting of 77.9 GW thermal, 29.5 GW hydro, 2.7 MW nuclear and 1.8 GW wind. The share of hydro decreased compared to total from 33% in the year 1950 to 26.33% in the duration 2003-2004. In the 10th year plan (2002-2007), India has targeted to add 14393 MW hydro, 25417 MW thermal and 1300 MW nuclear /cea.nic.in/, /powermin 1991-2005/.

India has 14 small nuclear power reactors in commercial operation and nine are under construction. Nuclear power supplies 3.3% of India's total electricity generation in 2003 from the nuclear capacity of 2.5 GWe (of 110 GWe total) and this is expected to increase steadily as new plants come on line. Fuel situation and environmental concern drives India for investment on nuclear electricity, and 25% nuclear capacity contribution is foreseen by 2050, from one-hundredth times in the year 2002 /npcil.nic.in/. The nation has a flourishing and largely indigenous nuclear power program and expects to have 20000 MWe nuclear capacities by 2020. The long-term goal of India's nuclear program is to develop an advanced heavy-water thorium cycle, as the reserve of thorium is six times more than uranium. Kakrapar-1 was the first reactor in the world to use thorium and operated for 300 hours.

2.2.4 Renewable

There is a large potential of renewable energy in India. The estimated aggregated potential for these energy resources are more than 130000 MW /mnes/ both for power generation and thermal applications. The small hydro has (<25 MW) potential of 15 GW /mnes/, tidal power has potential of 5 GW /mnes.AkshayaUrja/, wind 45 GW /mnes/, biomass 55 GW /mnes/, geothermal 10 GW /mnes/, waste 2.7 GW /mnes/ and solar potential is very high as India is exposed to high intensity of sunlight. The installed capacity of wind technology reached 1.175 GW in year 2000, 0.226 GW bagasse based in year 2000, 0.015 GW waste based in year 2000 and 0.038 GW biogas based in year 2000 /mnes/, /power.ministry/.

There is continuous installation and increase of the hydro power capacity in India, which has been reached to 22439 MW at present but the share of hydro power has been reduced to 25% in terms of total installed capacity for power generation from 52.62% in 1966. The share of hydro in the total installed capacity was around 63% in the year 1947 and follows the decrease in trend till today. In order to maintain the balance between hydro and thermal power, ministry of power has taken a step and devised some policy majors for accelerated development of hydropower in the country. Also development of small hydropower at an accelerated pace is one of the tasks inside the policy /powermin 1991-2005/. The potential of different renewable energy carriers for India is provided in the Table 2-1. The projection of electrical potential is for the electricity production from renewable energy carriers. The reserve and resource potential of biomass is 198 Mtoe /earthtrends.ene.356/, dung is 99.84 Mtoe /Kumar, Ayyappan 1998/ and other energy carriers are provided in Table 2-2.

Table 2-1: The estimated renewable energy potential of India

Maximum electrical and thermal potential by energy carriers					
	Projections for electrical potential [MW]				
Source	/MNES/	/DOE.india/	/TERI/	/mnes.AkshayaUrja/	Model
Small Hydro<25MW	15000		10000		15000
Hydro	135000	150000			135000
Hydro Pump Storage	94000	90000			94000
Tidal Power				5000	5000
Solar					20000
Wind	45000	45000	20000		45000
Biomass	16500	20000	17000	35500	55000
Bagasse	3500	3500	3500		
Biomass Gasifier				16000	16000
Geothermal		10000		5800	10000
Waste	1700	0	1700	2700	2700
Biogas					60
Tidal Power	9000				0
Ocean Thermal Power	50000				0
Sea Wave Power	20000				0

Table 2-2: The estimated renewable and hydro energy potential of India

Potential by energy carriers						
Carriers	Source	Unit	Reserve	Resource	Rev.&Res.	Model
Hydro		Mtoe			60.00	
Hydro		Mtoe			51.59	51.59
Wind		Mtoe			25.00	25.00
Geothermal		Mtoe			10.00	10.00
Solar	/mnes.invopp/	TkWh			5000	
Solar	/mnes.invopp/	Gtoe			429.92	
Biomass	/PETROFED/	Mton			540.00	
Biomass	/PETROFED/	Mtoe			188.69	
Biomass	/earthtrends.ene.356/	Mtoe			198.00	198.00
Dung	/Kumar, Ayyappan 1998/	Mton			1000.00	
Dung	/Kumar, Ayyappan 1998/	Mtoe			99.84	99.84

2.2.5 CO_2 emission

India is currently the fifth-largest carbon emitter in the world (behind the United States, China, Russia, and Japan) and accounts about 4.2% of the world’s total fossil fuel-related carbon dioxide emissions. Carbon dioxide emission has increased by about 60% within past decade, and is about nine times higher than they were forty years ago. The rate of increase of CO_2 emission is contributed mainly by utilisation of higher share of coal in power sector and reduction of hydropower generation in generation mix. Emission reduction can be curtailed by an increased share of hydro and nuclear in energy mix, so government of India has planned and constructing large amount of hydro and nuclear power capacity to overcome Green House Gas (GHG) problem. Also India is trying to implement demand side management and looking for CDM options.

2.3 Energy situation of China

2.3.1 General overview, GDP and population

The geographical area of China is around 9.6 million square kilometer, i.e., one-fifteenth of world’s total landmass, third largest country in the world, next to Canada and Russia, slightly greater than United States. It is a land of extremely diversified climatic condition, tropical in south to sub-arctic in north. The northern part of Heilongjiang province has no summer, Hainan island has a long summer but no winter, the Huaihe river valley features four distinct seasons, the western part of the Qinghai-Tibet plateau is covered by snow all year around, the southern part of the Yunan-Guizhou plateau is spring-like all the year, and the northwestern inland region sees a great drop of temperature in the day. The temperature difference of 40 degree centigrade occurs in winter between the north and south part /chinatoday.general/.

China is the second largest economy in world after US in terms of Purchasing Power Parity (PPP) and fastest growing economy. The GDP has been increased fourfold from the year 1978 but GDP per capita is still low compared to world average /cia.china/. Export of iron, steel and cement in industry sector and domestic production in residential sector play a major role for the high rate of GDP growth. The GDP of China was 1842 €(00), 3418 €(00) and 5091 €(00) in year 1990, 1995 and 2000 respectively /Criqui 2001/. Population of China increased tremendously towards the beginning of sixties and continued to increase rapidly till mid-nineties. Total population was 1143.33 million according to national population census 1990 and reached 1259.1 million in the year 1999, which is about 22% of total population of world /chinatoday.general/, /chinastat 1995/.

2.3.2 Energy consumption

The incremental energy demand for the next decade is projected to be among the highest in the world, by highest GDP and population growth rate. The country is the third-greatest energy producer in the world behind US and Russian Federation and accounts 9.5% of the world’s annual total energy production /cslforum.china/ and was the second largest energy consumer in the world, next to United States and sweep over to Russian Federation in year

1999 accounting 10% of the world's total energy consumption. However the per capita energy consumption is in lower side (32.525 GJ in year 1987 against the world average 66.752 GJ and OECD countries 207.424 GJ) /Farinelli et al. 2001/. The primary energy consumption by China in the years 1990, 1995 and 2000 was 630 Mtoe, 820 Mtoe and 950 Mtoe respectively /WEO 2002/.

China's total primary energy production has reached to 1239 million tonnes of coal equivalent (Mtce), which is 52.2 times the figure of 1949. Within the total primary energy production, coal accounts for 75%, petroleum 17.5%, natural gas 1.9%, and hydro 5.6%. The position of the country in coal production has changed from ninth place in 1949 to first in 1991 in world, while petroleum and natural gas have gone up from 27th to 5th /energy.china/. Biomass energy consumption in China has been estimated as about 185 million tonnes of oil equivalent (Mtoe) in year 1993 /Jingjing et al. 2001/. It is estimated that annually about 210 Mtoe of agricultural residues and about 70 Mtoe of animal wastes are potentially available for energy use in China /AIT.SIDA/.

Total final energy demand of China in past and at present are figured by IEA differently in different years. Total final energy consumption was around 505 Mtoe in 1990, 697 Mtoe in 1995 and 785 in year 2000. In total final energy consumption, residence holds largest share in year 1990 but in year 2000 industry holds biggest share. All end use sectors increas their share from 1990 to 2000. Demand of industry sector energy consumption increased from 152 Mtoe from 1990 to 314 Mtoe in 2000. Commcere sector increased from 38 Mtoe in year 1990 to 59 Mtoe in year 2000. Energy consumtpion was 244 Mtoe in year 1990 and 296 Mtoe in year 2000 by residence sector. Transport energy demand increased from 45 Mtoe in 1990 to 84 Mtoe in year 2000. Likewise non-energy use consumption was 26 Mtoe in year 1990 and 32 Mtoe in year 2000. High GDP growth and increase in standard of living incraeses the energy demand. Residence sector of China passes through the phase of polluting fuels in residence sector for the smoke and indorr pullution related mortalities and diseases.

2.3.3 Electricity production sector

Total electricity generation in 1990 was 621.1 TWh, of which thermal power provided 494.4 TWh (79.6%) /www.edu China/. The electricty demand by China in year 1990 was 625 TWh, in 1995, it was 989 TWh and in year 2000, it was 1387 TWh /WEO 2004/. Electricity production augmented more than doubled between 1987 and 1997 (1134 TWh), with coal-fired generation since the overwhelming source of electricity in China. The annual growth rate of electricity generation was 7.5% during the 1980s. Electricity consumption per capita of China has increased from 306 kWh in 1980 to 549 kWh in 1990, with an average annual growth rate of 6.5 per cent /www.edu China/.

China’s electricity industry has grown up just from installed capacity of 1.85 GW in 1949 and reached to 236.54 GW in 1995, 298.5 GW in 1999, 315 GW in 2000 and 353 GW in 2002 /Cho 2004/. The total capacity in year 2000 was composed of 77 GW hydropower (15%), 235 GW thermal power (83%), 2 GW nuclear power (1%) and rest was contributed by renewables /eva.china/. Installed electricity generating capacity in year 1995 was 227 GW, of which 70% was coal-fired, 23% by hydro, 6%by oil-fired and remainder contributed jointly by gas and nuclear.

Currently China has the second greatest amount of installed electricity capacity in world, accounting about 9.4% of the world’s total installed generating capacity and behind only to the United States. The official plans envisaged expanding electricity generation capacity to 370 GW in 2005 /Anonymous 2001/, 530 GW in 2010 and 800 GW in 2020 /Blackman and Wu 1997/. In chinese power generation sector coal contributes around four-fifths of its electricity generation but China’s 10th Five Year Plan has set the target of increasing the share of hydroelectric, natural gas, nuclear, and other clean fuels in the total power generation mix share from the current 26% to 31%.

China’s development of nuclear power started in commercial operation from year 1993 at Quinshan with 279 MW PWR reactor /worldenergy.china/. At the end of 1999, China’s nuclear generating capacity was 2167 MW_e, output of the power plant was 1.2% of total electricity generation. More seven nuclear units, two PHWRs and five PWRs with aggregated capacity of 5.4 GW was built. China currently has nine nuclear reactors in operation, with a total installed capacity of more than 6,900 MWe and in 10th five year plan (covers period 2001-2005) has set a goal of 60 billion kWh, grows up 266% from 2001 /DOE.china/. The official plan of China calls for 20 GW of nuclear capacity by the year 2010 and between 40 to 50 GW by 2020 /WEO 1998/. China reported the completion of a 10 MW prototype high-temperature gas-cooled reactor at the end of 2000 /worldenergy.china/.

2.3.4 Renewable

China has high potential of renewable resources. China has the small hydro (<25 MW) potential of 120 GW /hrcshp.rural/, tidal power potential of 21.7 GW /Ping Zhou Jia/, wind potential 253 GW /Ping Zhou Jia/, biomass potential 51.51 GW till 2020 /Jingjing et al. 2001/, geothermal potential 10 GW /DOE.china/, waste potential 23.33 GW /Jingjing et al. 2001/. Solar potential is very high as China is exposed to high intensity of sunlight. The existing capacity in year 2000 for solar PV was 0.07 GW, wind 0.345 GW, biomass 0.412 GW, geothermal 0.106 GW, waste 0.015 GW and biogas was 0.0025 GW.

China has vast hydropower resources contributed by three great rivers, the Huang Ho (Yellow River) in the north, the Chang Jiang (Yangtze River) in the center and the Pearl River in Guangdong. China has the largest hydroelectric potential in the world estimated as

675 GW, of which 290 GW is economically exploitable, and from the total exploitable potential 56 GW, 60 GW and 70 GW are actually exploited in years 1996, 1997 and 2000 respectively. As of January 2001, the estimated installed hydroelectric capacity totaled about 79,000 MWe, and Chinese government forecast this figure to climb up to 100,000 MWe by 2005 /DOE.china/. The 10th Five Year Plan calls for a 48% rise in hydropower production by 2005. By 2020, hydro-power capacity may reach almost 200 GW, including world's biggest hydro-electric plant, 18.2 GW Three Gorges project on the river bed of Yangtze river /WEO 1998/. More than 17% of China's total electricity production is supplied by hydropower at present. China plans to increase its electric power capacity by between 8% and 9% per year to meet growing demand and continuous addition of hydro power plants taking place. The potential of different renewable energy carriers for China is provided in the Table 2-3. The projection of electrical potential is for the electricity production from renewable energy carriers. The reserve and resource potential of geothermal is 2.204 Gtoe /Ping Zhou Jia/, biomass is 280 Mtoe /AIT.SIDA/ and other energy carriers are provided in Table 2-4.

Table 2-3: The estimated renewable energy potential of China

Maximum electrical and thermal potential by energy carriers									
	Projections for electrical potential [GW]								
Source	/Ping Zhou Jia/	/sdep.cei. china/	/Jhirad, Langer 1997/	/eva. china/	/worldenergy. china/	/DOE. china/	/Jingjing et al. 2001/ (till 2020)	/hrcshp. rural/	Model
Small Hydro	76			180				120	120
Hydro		378			290	300			378
Hydro Pump Storage									
Tidal Power	21.7	20	9.83						
Wind	253	1600	250		3200	250			253
Biomass							48.5		51.51
Bagasse							2.38		
Biomass Gasifier									
Geothermal				6.744		10			10
Waste							23.33		23.33
Biogas							0.63		0.63
Ocean Thermal									
Sea Wave									

Table 2-4: The estimated renewable and hydro energy potential of China

Potential by energy carriers						
Hydro	/china.hpyb 1998/	Twh/a			7845	
Hydro	/china.hpyb 1998/	Mtoe			675	
Hydro		Mtoe			145	195.00
Wind		Mtoe			95	95.00
Geothermal	/Ping Zhou Jia/	Mtoe			2204	2204.00
Biomass	/Jingjing et al. 2001/	PJ			5617	
Biomass	/Jingjing et al. 2001/	Mtoe			134	
Agr.&Fore. Residue	/CRED Team 2001/	Mtoe			291.30	
Biomass	/Ping Zhou Jia/	Mton			858	
Biomass	/Ping Zhou Jia/	Mtoe			140.54	
Dung		Mton			538	
Dung		Mtoe			54	54

2.3.5 CO_2 emission

In China, carbon dioxide emissions per person have climbed approximately from 2.08 tonnes in year 1990 to 2.28 tonnes in year 1996, 2.42 tonnes in year 2000 /WEO 2004/, which is much lower than the Japanese figure of 9.36 tonnes per capita or the US figure of 20.05 tonnes per capita in year 1996, but the growth rate of 24.5% is high compared to the Japanese 9% or the US 2.8% over the same period /IEA.CO2 1998/. In 1996, China accounted 13.8% of the total world energy-related CO_2 emissions, compared to 23.4% of the United States, 17.8% of OECD Europe and 5.2% of Japan. Between 1990 and 1996, China's energy related CO_2 emissions increased by 33%, from 2,362 million tonnes to 3,142 million tonnes /IEA.CO2 1998/. China is currently responsible for slightly more than one-eighth of the world's total fossil fuel-based carbon emissions, ranking it second in the world behind the United States.

2.4 Challenges associated with world energy system

Various challenges are associated with world energy system. The challenges are categorized from economic, environment, technical and social point of view and provided below.
Economic point of view:

- Lacking fund towards learning investment.
- Economical exploitation of methane from gas hydrates.
- Economic transport of natural gas, hydrogen and LNG.
- Backup technologies for energy security by intermittent technologies.
- Integration of less elusive energy (oil shale) in future energy system.

- Massive investment in extraction and mining (fossil fuels) and exploration of reserves in competitive price.

Environment point of view:

- Well-planned utilisation of unusable, unarable and desert areas.
- Providing increase in electricity demand to developing world without significant environment damage and mere health impact.
- Reduction of GHGs emission from the atmosphere.
- Control of global warming, sea level rise and unnatural disasters.
- Less dependent on fossil fuel or reduction of fossil fuels use.
- Switching from environmental deteriorating to climate compatible fuels.
- Switching from energy and emission intensive activity to eco-efficiency activity.

Technical point of view:

- Switching from heavy dependence on crude oil.
- Integration of H_2, one of the clean energy options of the future energy in various sectors.
- Integration of intermittent renewable technologies, micro-turbine, fuel cell and advanced combustion engine into the power grid.
- Tapping of energy carrier like solar, wind, geothermal, wave and environmental heat from renewable energy prone areas.
- Implementation of emission reduction strategy through carbon captures technologies and storage by devices.
- Stepping towards energy saving and energy efficiency improvement measures.
- Incorporation of biotechnology in power production and synthetic fuel production sector.
- Development of fusion technology and its integration into power sector.
- Thorium cycle development in three-stage nuclear power program.
- Reduction of high T&D loss in power sector, which arises to some extend by pilferage in developing regions.
- Feeding power to remote hilly areas and extract the renewable energy from unreachable locations.
- Improvement of power quality (by Flexible AC Transmission Systems (FACTS) devices) to recover from blackouts and brownouts.
- Long-term prospect of geothermal heat pump (depending on technological and economic viability of Hot Dry Rock (HDR)).
- Diffusion of learning technologies especially new, efficient and climate compatible.
- Integration of regional grids to minimize the installed capacity.

Social point of view:

- Diversification from communal (mass) transport mode to individual mode.

- Preference on cluster family than individual, apartments than sinlge house based on geological situation and change in human behaviours.
- Handling of nuclear waste and catastrophe free operation of nuclear power plants.
- Noise problem by wind turbine (television and radio interference, danger to birds, visual effect, etc.).

2.4.1 Challenges associated with India energy system

More or less all challenges of world energy system are applicable to India. Apart from that it has more challenges integrated in its energy system like reduction in time spend for collecting wood, empowering women, cutting down the harmful household smoke exposure, diminution of forest clearing and its ecological consequences /worldenergy.rural/. Apart from these, India has biggest hurdles on theft of the power and heavy loss in T&D. The transmission and distribution system needs to be restructured for the minimum loss in wires. Frequently load shading; brownouts and blackouts are the major problems in the electricity grid of India. Construction of gas grid for the household supply is another one challenge to Indian energy system. Penetration of energy efficient technologies in every sectors and development of the awareness on rational use of energy among the people and conservation of energy are the major challenges inside this regional energy system.

2.4.2 Challenges associated with China energy system

More or less all challenges of world energy system are applicable to China. Apart from that it has more challenges integrated in its energy system like reducing harmful household smoke exposures, reducing forest clearing and its ecological consequences /worldenergy.rural/, reduction of transmission and distribution losses, tapping of solar energy, tapping of hydro energy and wind energy from far-flung south-west region, utilization of the coal produced in north-east part of the country, etc. Penetration of energy efficient technologies in every sectors and development of the awareness on rational use of energy among the people and conservation of energy are the major challenges inside this regional energy system.

2.5 Overview on existing global models and scenarios

Since mid 70’s, energy systems modeling have been identified as an extremely valuable tool within economic analysis of energy issues. National, regional and global energy models developed during the past have been extensively used by administrative authorities to plan energy system extension and expansion, as well as by the private sector to anticipate changes in the market structure. In some cases, an *ad-hoc* or issue based specific energy model has been developed to deal with a particular issue or target. In other cases, general-purpose models have been developed and these models are flexible enough to solve a wide variety of problems /Acropolis 2001/.

Overview on existing models gives the overall idea about the energy demand by different models for different sectors in past, at present and in the future. Also the models reflect the reserve and resource to satisfy the demand in future, the status of energy carriers in the sectoral energy demand and the technology that prevail the energy supply in different regions and different sectors. There are some existing global models developed by various research groups around the world, to predict the world energy demand in future and the energy structure. Some of the global energy models those are developed in various corner of the world are presented below.

2.5.1 ETP model

Energy Technology Perspective (ETP) model belongs to the MARKAL (MARKet ALLocation) family of bottom-up system engineering model; which has been developed during the past 30 years by the Energy Technology Systems Analysis Programme (ETSAP), one of the IEA's Implementing Agreements; based on a combination of linear programming and mixed integer programming that minimises an objective function calculated as a sum of annualised costs of an energy system that satisfies certain energy demand under given user constraints (e.g., the attainment of certain production levels, the availability of certain technologies, etc.). The model solution represents the equilibrium that would be achieved in an ideal market and (according to neoclassical welfare economics) would maximise the welfare. Also it is a model of market mechanism simulation. The model characteristics are based on maximisation of the consumer or producer surplus.

The main idea and objective behind the development of the model is to develop an analytical framework to study how deployment of new energy technologies can affect fuel markets, GHG emissions, energy security, designing promising policies, future investment decision and identify technology options for long term.

The ETP model is a micro-economic model and represents part of the world economy. The whole world is divided into 15 regions. The model covers time horizon from 2000 to 2050 with 11 periods and each period having time duration of 5 years. It has region specific technology database, bearing around 1800 technologies and covers the energy service from extraction to end-use. It includes region specific resource, technology availability, technology cost and discount rate. The model assumed the development of population and GDP till 2030 from WEO and extrapolated beyond that /Difiglio and Gielen 2004/.

The Reference Energy System (RES), which is the graphical representation of the energy system, of ETP model consist of the interconnected flow of commodities from the extraction to useful energy demand /Gielen 2003/, where carriers in terms of energy, money, emission, etc., flows through the processes and the processes interconnect flows of different carriers.

2.5.2 SAGE, EFDA and TIAM models

The System for the Analysis of Global Energy markets **(**SAGE) energy economy model is based upon producers and consumers surplus of energy carriers. Like most equilibrium models; SAGE assumes perfectly competitive markets for energy carriers, where producers maximize profits and consumers maximize their collective utility. The result is a supply-demand equilibrium that maximizes the net total surplus (i.e., the sum of producers and consumers surpluses). It is based on partial equilibrium concept representing the market price of the commodity that is exactly equal to the marginal cost.

The time horizon was supposed to change from 2025 to 2050. The model considers eleven periods of five-year duration each. The first period extends from 1998 to 2002 and is called 2000 by reference to its middle year. Each year is divided into three seasons (winter, summer and intermediate) and further on day and night. Thus the model has six smallest time resolutions. The important exception is that all basis investments are assumed to occur at the beginning of each modelling period with the resulting installed capacity available throughout that period. The initial period calibrates the model to the latest comprehensive historical data available. No new investments are allowed in this period. Regions are connected by import and export of commodities. Population, GDP and GDP per capita are basic factors project the final energy demand /SAGE-II 2003/. This model is developed and used by Energy Information Administration (EIA) and published the projection of energy consumption result in the International Energy Outlook 2004 for fifteen regions or countries of the world.

The SAGE model is a technology explicit, multi-regional, partial equilibrium, elastic demand driven, limited foresight and *behavioural approach* for determining *market shares.* While the first four of these characteristics are inherited from its MARKAL predecessor, the last two (limited foresight and a behavior-based market share mechanism) are features that are unique to SAGE, and make the model a hybrid between optimizing and behavioral models. These two features have been added to depict the evolutionary nature of energy and technology markets.

In the complete RES of SAGE model, a node depicts each region, source, sink, technology, and demand, and each commodity (energy carrier, energy service, emission) is depicted by a link. Energy commodities are extracted, exported or imported; processed by technologies, and eventually consumed by end-use technologies to satisfy a set of demands for energy services. The transformation of commodities passes through different level like primary (represents the production), secondary and tertiary (represents the level of transformation). The resource has been modelled in three different steps; but for oil, it considered three steps for each discovered reserves, undiscovered reserves, and unconventional sources.

Fifteen regional global model developed in the model generator TIMES has been developed at Montreal, Canada by Prof. Loulou and his group having two different names, one is EFDA, in which the group of Prof. Loulou and his group is responsible and the other one is TIAM, in which both Prof. Loulou and IER, University of Stuttgart, Germany are working together. These models have perfect foresight (clairvoyant in nature) and are the derived model from the SAGE. Thses models are developed under ETSAP paradigm.

2.5.3 POLES model

The dynamics of the Prospective Outlook on Long-term Energy Systems (POLES) model is based on a recursive (year by year) simulation (myopic) and partial equilibrium framework, with endogenous international energy prices and lagged adjustments of energy supply and demand of world regions, supply with lagged adjustments to prices and a feedback loop through international energy prices. It has been developed under EU research programme; the model is fully operational since 1997. The model has been used for policy analyses by the French Ministry of Environment; and by the Organisation of EU-DGs Research, Environment and TREN (Trust Environmental model).

The main objective of the model is to project energy demand, supply and price of regions for a long term (till 2030), to study CO_2 emission, to calculate Marginal Abatement Cost (MAC) curves of regions, and emission trading, under different market configurations and trading rules; and to realise the technology diffusion under exogenous and endogenous technological change in the context of CO_2 abatement policies.

In the current geographic dis-aggregation of the model, the world is divided into thirty-eight countries or regions, allowing to identify the key world regions of most energy studies. For each region, the model articulates four main modules dealing with final energy demand by main sectors; new and renewable energy technologies; the conventional energy and electricity transformation system; and fossil fuel supply.

The POLES model is a global sector-wise model of the world energy system. RES of POLES model is a hierarchical structure of interconnected sub-models at the global, regional and national level /Criqui 2001/.

In the detailed demand model for the main countries or regions, the consumption of energy is disaggregated into homogeneous sectors, which allow to identify the key energy intensive industries, the main modes of transport, the residential and tertiary activities.

Energy consumption in each sector is calculated for substitutable fuels on one hand and for electricity on the other, while taking into account specific energy consumption (electricity in electrical processes and coke for the other processes in steel-making, feedstock in the chemical sector, electricity for heat and for specific uses in the Residential and Tertiary sectors).

2.5.4 MESSAGE model

Model for Energy Supply Strategy Alternative and their General Environmental impact (MESSAGE) is a dynamic linear programming model with a mixed integer option, systems engineering optimization model, developed at IIASA /Messner and Strubegger 1991/; /Strubegger and Reitgruber 1995/ were used for medium- to long-term energy system planning, energy policy analysis, and scenario development /Messner and Strubegger 1995/. The model provides a framework for representing an energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation. Current version of the model provides information on the utilization of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy. It is a technology rich model and consists of around 1600 technologies. The model configures the evolution of the energy system from the base year (1990) to the end of the time horizon 2100 (in ten year steps). In MESSAGE model, world is divided into four parts of 11 regions.

In the course of a model run MESSAGE determines how much of the available technologies and resources are actually used to satisfy a particular end-use demand, subject to various constraints, while minimizing the total discounted energy system costs. Operationally, MESSAGE configures the energy system of a set of regions over a certain time horizon in such a way as to minimize the net total cost (or equivalently maximize the net total surplus) of the system with satisfying a number of constraints.

The RES of MESSAGE model includes all possible energy chains and the energy carriers are distinguished by primary, secondary and final. Resource extraction is categorised as the primary energy carrier and the product out of the primary energy carriers is termed as secondary energy carriers and the consumption by the demand sector termed as final energy. Extraction of resource, conversion of the primary energy carriers and final energy consumption takes place by various technologies. Some technologies are adopted to produce the final energy out of secondary energy carriers. The RES shows how individual technologies are connected to each other through their inputs and outputs and across different stages of energy conversion, transformation and transport.

2.5.5 WEM model

International Energy Agency at Paris has developed twenty regional World Energy Model (WEM) and since 1993 IEA is providing long-term energy projection of the regions using this model. This model is going through continuous modification, evolution, extension and expansion. WEM is a mathematical model made up of five main modules, i.e., final energy demand, power generation, refinery and other transformation, fossil fuel supply and CO_2 emissions /WEO 2004/. The model contains the refinery module to project the oil products demand development in the regions and refinery capacity development also. The module calculates and balances the global oil products. The model integrates fossil fuel modules like coal; oil and natural gas to know the demand, production, import and export of fossil fuels by regions. At present the model projects the energy demand by end use sectors of industry, transport, others and non-energy use. It also projects the power generation and related capacities; input to power generation; transformation, own use and losses; and total primary energy supply for a long horizon till 2030. The main exogenous assumption for the model is economic growth, demographics, international fossil fuel prices and technological developments. Supply modules serves as the input for primary energy demand. The drivers of energy demand are taken based on various indicators and that to region specific. The general indicators like GDP, GDP/capita, vehicle stock, passenger- and ton-kilometer are taken for all the regions and demand specific activity like agriculture; and iron and steel are used less often for Non-OECD countries. The model is based on general eqillibrium approach of linear programming with extension of MIP approach facility.

2.5.6 AIM, ASF, IMAGE, MARIA and MINICAM models

The Asian-Pacific Integrated Model (AIM) is a large-scale model for the scenario analyses of greenhouse gas emissions and the impacts of global warming in the Asian-Pacific regions. It comprises three main modules: the GHG emission model (AIM/emission), the global climate change model (AIM/climate) and the climate change impact model (AIM/impact). It was originally bottom-up model and later integrated to top-down models. Time horizon of the model is from 1990 to 2100 with five-year time step from 1990 to 2030 and rest periods are defined as 2050, 2075 and 2100 /sres.ciesin/.

The Atmospheric Stabilization Framework (ASF) model consists of nine world regions. The model provides emission estimation of world regions and includes energy, agricultural, deforestation, GHG emissions and atmospheric models. Also it consists of four end use sectors: residence, commerce, industry and transport /sres.ciesin/.

IMAGE2 model consists of three inter-linked models: the Energy-Industry System (EIS); the Terrestrial Environment System (TES); and the Atmosphere-Ocean System (AOS). The *Energy-Industry System (EIS)* sub-module computes the emissions of greenhouse gases for 13 world regions from the Targets Image Energy Regional (TIMER) simulation model. The *Terrestrial Environment System (TES)* simulates global land-use and their effect on emissions of greenhouse gases, ozone layer, and carbon fluxes between the biosphere and the atmosphere /sres.ciesin/.

The Multiregional Approach for Resource and Industry Allocation (MARIA) is a compact integrated assessment model to assess the interrelationships among economy, energy, resources, land use and global climate change. The original model was the DICE model, developed by W. Nordhaus. MARIA has been developed to assess the technology and policy options to address global warming. It is an intertemporal non-linear optimization model dealing with the international trading among seven regions of world /sres.ciesin/.

MiniCAM is a small Integrated Assessment Model that estimates global greenhouse emissions. It is developed by the Global Change Group at Pacific Northwest Laboratory and undergoes regular modification. The model consists of 14 regions and integrated macro economic activity; energy; agricultural; emissions; and climate change integrated with its impacts within it /sres.ciesin/.

Comparion of different models developed across world by their description, regions considered inside, model horizon of the study, programming approach and degree of the disaggregation on sectors are presented below. TIMES G5 model is developed to know the energy situation, energy consumption and the emission of CO_2 for different regions. Also the model development has been done to taste the learning concept on global learning subject to technology gap.

2.5.7 Comparison of models by criterias

The description of some energy models developed around world and their criteria is summarized in the Table 2-5. The models are compared from the point of the top-down and bottom-up; number of regions considered inside the study; time horizon considered for the study; optimization criteria considered and the degree of disaggregation of the end use sectors. The models narrated below are developed on the MARKAL or other environment model generator and some models are myopic and some are clairvoyant. There are few global models developed around world on TIMES model generator. But the TIMES G5 model developed on TIMES code has many advantage within it. It is perfect foresight model with extension of learning theory analysis inside it.

Table 2-5: Comparison of models by criteria

Model	Description	Region	Time horizon	Programming/Optimisation criteria	Degree of disaggregation
ETP	Bottom-up	15	2000-2050	Partial equilibrium with MIP facility	Disaggregated
SAGE	Bottom-up	15	1990-2025	Period by period market simulation/partial equilibrium	Disaggregated
POLES	Bottom-up	38	1990-2030	Recursive simulation and partial equilibrium	Disaggregated
MESSAGE	Bottom-up	11	1990-2100	Dynamic linear with MIP approach/MACRO	Disaggregated
WEM	Bottom-up	20	1990-2030	Partial equilibrium with MIP facility	Disaggregated
AIM	Bottom-up/top-down	21	1990-2100	Dynamic optimization model	Disaggregated
ASF	Bottom-up	9	1990-2100	Supply-demand balance by iterative search technique	Disaggregated
IMAGE	Bottom-up	13	1990-2100	Simulation model	Disaggregated
MARIA	Bottom-up	7	1990-2100	Inter-temporal non-linear optimisation	Disaggregated
MINICAM	Bottom-up	14	1990-2100	Integrated assessment/partial equilibrium	Disaggregated

2.5.8 Socio economic situation of existing studies

The socio-economic parameters like population and GDP, those are the drivers of energy demand are reflected inside this study by different sources, to understand the accuracy of the development of population and GDP inside this study. The population and GDP development in the existing studies are presented in Table 2-6. The growth rate of population considered by /IEO 2004/ from 2001 to 2025 is 1.2%/a for India, 0.5%/a for China, 0.4%/a by industrialised countries and 1.2%/a for developing countries. The world population will be 11.7 billion in 2100, approximately two-fold increase over 1990 (5.1 billion) and the population of world will pass around 10.4 billion in year 2050. Also the assumption for the share of OECD region's population in world will decline from 16% in 1990 to 8% in 2100 /Ito et al. 2000/. According to the work of /Morita et al./, the world population will vary between 11.7 to 15 billion in 2100 and will attain 9 billion in year 2050, whereas the second leading populous region India will touch 1.65 billion in year 2100 /Rajesh et al. 2002/. The world population and GDP of different models considered in IPCC study are provided in Table 2-7.

Table 2-6: Population and GDP of existing studies (1)

Average population growth rate [%/a]

Region	WEO, 2004				IEO, 2004
	2002-2010	2010-2020	2020-2030	2002-2030	2001-2025
Europe	0.30	0.10	0.00	0.10	
OECD	0.60	0.40	0.30	0.40	
Dev. Countries	1.40	1.20	0.90	1.20	
India	1.40	1.10	0.80	1.10	1.2
China	0.70	0.50	0.10	0.40	0.5
World	1.20	1.00	0.80	1.00	1

Average GDP (ppp) Growth Rate [%/a]

Region	WEO, 2004				IEO, 2004
	1990-2000	2010-2020	2020-2030	2002-2030	2001-2025
Europe	2.40	2.20	1.70	2.10	
OECD	2.70	2.20	1.80	2.20	
Dev. Countries	5.10	4.30	3.60	4.30	
India	5.60	4.80	4.00	4.70	5.2
China	6.40	4.90	4.00	5.00	6.1
World	3.70	3.20	2.70	3.20	3

Population [Million]

Region	WEO, 2004					IEO, 2004		
	1990	1995	2000	2020	2030	1990	2000	2025
EU25	428	445	449	449	444			
R_OECD	609	644	675	801	844			
R_NOECD	2206	2405	2616	3541	4005			
INDIA	850	932	1016	1307	1416	846	1017	1369
CHINA	1135	1205	1262	1431	1445	1155	1275	1445
WORLD	5228	5631	6019	7529	8154	5263	6061	7841

GDP (ppp) [Billion $(1995)]; WEO, 2004

Region	1990	1995	2000	2020	2030
EU25	7216	7831	8960	15059	17825
R_OECD	11674	13062	15547	27109	32579
R_NOECD	8520	8721	10022	21805	29257
INDIA	1513	1952	2568	6618	9796
CHINA	1676	2951	4388	15342	22710
WORLD	30599	34517	41485	85933	112166

(Source: /WEO 2004/, /IEO 2004/)

Table 2-7: Population and GDP of existing studies (2)

World population		Period											
Model	Unit	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
MESSAGE	Million	5262	6091	6891	7672	8372	8930	9367	9704	9960	10158	10306	10414
AIM	Million	5262	6091	6851	7612	8372	8855	9367	9638	9917	10129	10271	10414
ASF	Million	5256	6091	6870	7650	8277	9072	9367	9632	9771	10132	10341	10414
IMAGE	Million	5297			7869			9875					10360
MARIA	Million	5262	6091	6891	7672	8372	8930	9367	9704	9960	10159	10306	10414
MINICAM	Million	5293	6147	7009	7880	8640	9304	9874	10216	10453	10585	10501	10418
World GNP/GDP (market exchange (1990))													
Model	Unit	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
MESSAGE	Trillion US$	21	28	39	51	66	86	110	135	162	186	210	235
AIM	Trillion US$	21	28	36	48	67	86	111	134	161	187	211	237
ASF	Trillion US$	20	26	34	43	55	76	86	105	116	159	215	238
IMAGE	Trillion US$	21			41			76					199
MARIA	Trillion US$	20	27	37	50	64	83	108	130	156	182	206	233
MINICAM	Trillion US$	21	27	36	47	62	80	102	128	156	186	219	255

(Source: /IPCC, 2000/)

2.5.9 Scenarios and results of global models

The results of different scenarios developed by various organizations or groups inside their global model are presented in the Table 2-8 and Table 2-9. The result by different models shows the final energy demand, primary energy demand, cumulative CO_2 emission and energy intensity. The result also reflects the model horizon of the study and their milestone years. Table 2-8 and Table 2-9 reflects the result of different models contributed to the IPCC study. The models, those contributed to IPCC study and other studies given in the Table 2-8 and Table 2-9 are AIM, ASF, IMAGE, MARIA, MESSAGE, MINICAM, WEM/ETP, POLES and SAGE. Some models project the energy demand till 2100, e.g., AIM, ASF, IMAGE, MARIA, MESSAGE, MINICAM; some project till 2030, e.g., ETP, POLES; and some project till 2025, e.g., SAGE. The projection of total final energy and primary energy demand for whole world till 2100 by MINICAM model is highest among all models and the values are 26.685 Gtoe and 32.710 Gtoe respectively. The energy intensity is observed highest by IMAGE model and the value is 86% in year 2100 compared to 81% of MARIA, 70% of MESSAGE, 82% MINICAM, 81% ASF and 73% of AIM. The CO_2 concentration in the atmosphere till the year 2100 coming from the energy projection of different models are 639-ppmv by AIM model, 737-ppmv by ASF model, 547-ppmv by IMAGE model, 625-ppmv by MARIA, 535-ppmv by MESSAGE and 615-ppmv by MINICAM model.

Table 2-8: Scenarios and results of global models (1)

Indicator	Unit	Period										
		1990	**2000**	**2010**	**2020**	**2025**	**2030**	**2050**	**2060**	**2080**	**2090**	**2100**
B2 scenario of IPCC												
AIM (Asian-Pacific Integrated) Model												
Total Final Energy	Mtoe	6814	7255	8574	10042		11908	16031	17446	20292	21297	22351
Primary Energy	Mtoe	8973	10191	11981	14098		16546	22483	23890	28198	29309	30701
Cumulative CO2 Emission	GtC	0	75	162	262		374	643	794	1093	1239	1381
Energy intensity (final/primary)	%	76	71	72	71		72	71	73	72	73	73
ASF (Atmospheric Stabilization Framework) Model												
Total Final Energy	Mtoe	6239	7555	9470	12236		13669	16535	17375	19264	20522	21780
Primary Energy	Mtoe	7609	9079	11599	15118		17217	21414	22138	23939	25369	26798
Cumulative CO2 Emission	GtC	0	75	165	279		416	726	890	1227	1405	1592
Energy intensity (final/primary)	%	82	83	82	81		79	77	78	80	81	81
IM**AGE Model**												
Total Final Energy	Mtoe	6497			9014			12035				17333
Primary Energy	Mtoe	8221			12088			16227				20214
Cumulative CO2 Emission	GtC	0	75	161	259		366	601	723	958	1072	1183
Energy intensity (final/primary)	%	79			75			74				86
MARIA (Multiregional Approach for Resource and Industry Allocation) Model												
Total Final Energy	Mtoe	6631	7274	8871	10731		12771	17060	18731	21328	22102	22604
Primary Energy	Mtoe	8198	8886	10522	12496		14736	19997	22233	26444	27676	27912
Cumulative CO2 Emission	GtC	0	75	159	253		358	609	750	1048	1200	1352
Energy intensity (final/primary)	%	81	82	84	86		87	85	84	81	80	81
MESSAGE Model (IIASA)												
Total Final Energy	Mtoe	6566	7428	8656	10246		12114	15628	17278	20261	21702	22719
Primary Energy	Mtoe	8395	9750	11434	13507		15924	20763	23309	28287	30685	32419
Cumulative CO2 Emission	GtC	0	75	159	248		343	554	667	901	1026	1157
Energy intensity (final/primary)	%	78	76	76	76		76	75	74	72	71	70
MINICAM (Mini Climate Assement Model)												
Total Final Energy	Mtoe	6045	6841	8098	9817		11117	15210	17259	22380	24533	26685
Primary Energy	Mtoe	8032	8946	10582	12941		14941	20491	23048	28726	30718	32710
Cumulative CO2 Emission	GtC	0	75	160	256		366	613	748	1034	1181	1329
Energy intensity (final/primary)	%	75	76	77	76		74	74	75	78	80	82

(Source: /WEOs/, /IEO 2004/, /IPCC 2000/, /WETO 2003/)

The projection of primary energy demand by MESSAGE model is until 2100 and by ETP and POLES is restricted till 2030. The primary energy demand by MESSAGE model remains always in lower side compared to other models. The projection of primary energy demand by ETP models remains in higher side compared to POLES model during the initial period of the model horizon but towards the end periods of the model, the reverse phenomenon takes place. The comparison of primary energy demand by different models is portrayed in Figure 2-3.

Table 2-9: Scenarios and results of global models (2)

Indicator	Unit	Period					
		1990	2000	2010	2020	2025	2030
Other Scenarios							
WEM/ETP Model of IEA							
Reference Case							
Total Final Energy	Mtoe	5773	6908	8281	9788		11230
Primary Energy	Mtoe	8734	10090	12193	14405		16431
Total CO2 Emission	Mt	20123	22738	27817	33226		38214
Energy intensity (final/primary)	%	66	68	68	68		68
Alternate Scenario							
Total Final Energy	Mtoe	5773	6908	7976	9181		10110
Primary Energy	Mtoe	8734	10090	11728	13345		14654
Total CO2 Emission	Mt	20123	22738	26198	29583		31686
Energy intensity (final/primary)	%	66	68	68	69		69
POLES Model, Reference Case							
Total Final Energy	Mtoe	6270	7172	8682	10425		12132
Primary Energy	Mtoe	8530	9953	12111	14611		17213
Total CO2 Emission	Mt	20843	23781	29376	36738		44498
Energy intensity (final/primary)	%	74	72	72	71		70
SAGE Model of EIA							
Reference Case							
Primary Energy	Mtoe	8779.1	10051.6	11863.3	14307.6	15696.0	
Total CO2 Emission	Mt	21536	23536	27715	33541	37124	
High Economic Growth Case							
Primary Energy	Mtoe	8779.1	10051.6	12374.9	15867.3	17890.8	
Total CO2 Emission	Mt	21536	23536	28925	37345	42551	
Low Economic Growth Case							
Primary Energy	Mtoe	8779.1	10051.6	11283.8	12836.0	13654.9	
Total CO2 Emission	Mt	21536	23536	26360	29960	32032	

(Source: /WEOs/, /IEO 2004/, /IPCC 2000/, /WETO 2003/)

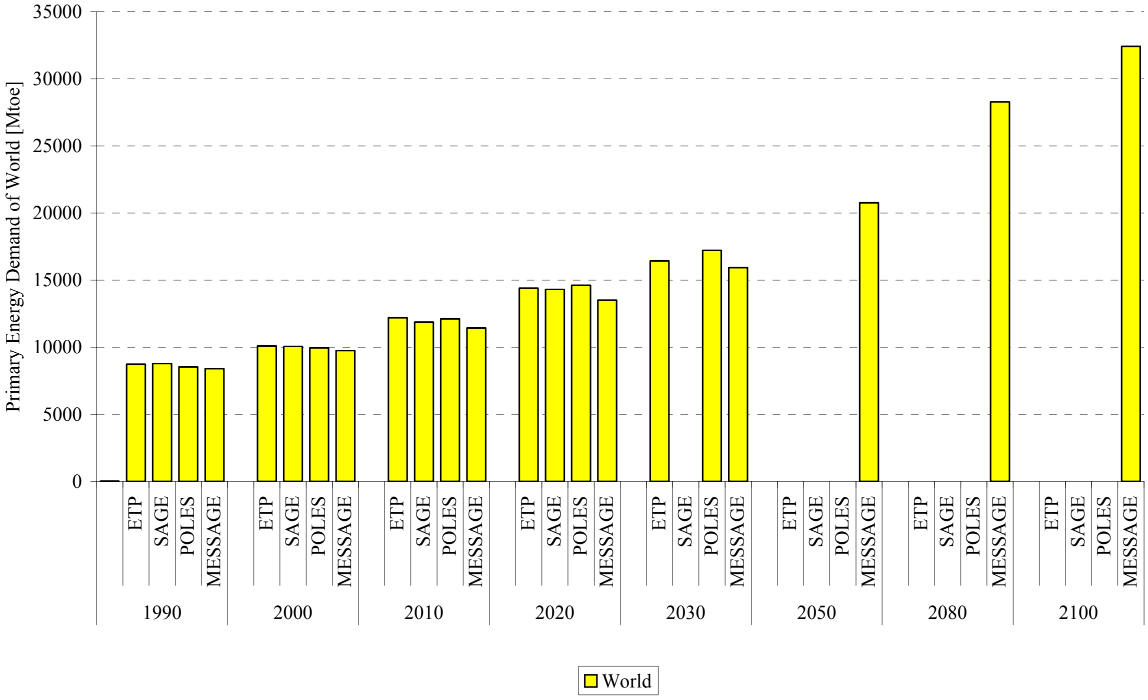

Figure 2-3: World primary energy demand projection by different models

Total final energy demand by ETP model remains always in lower side compared to other models utill the period 2030. The projection of total final energy demand by MESSAGE model remains in higher level compared to others, with the exception of the period 2020 as depicted in Figure 2-4.

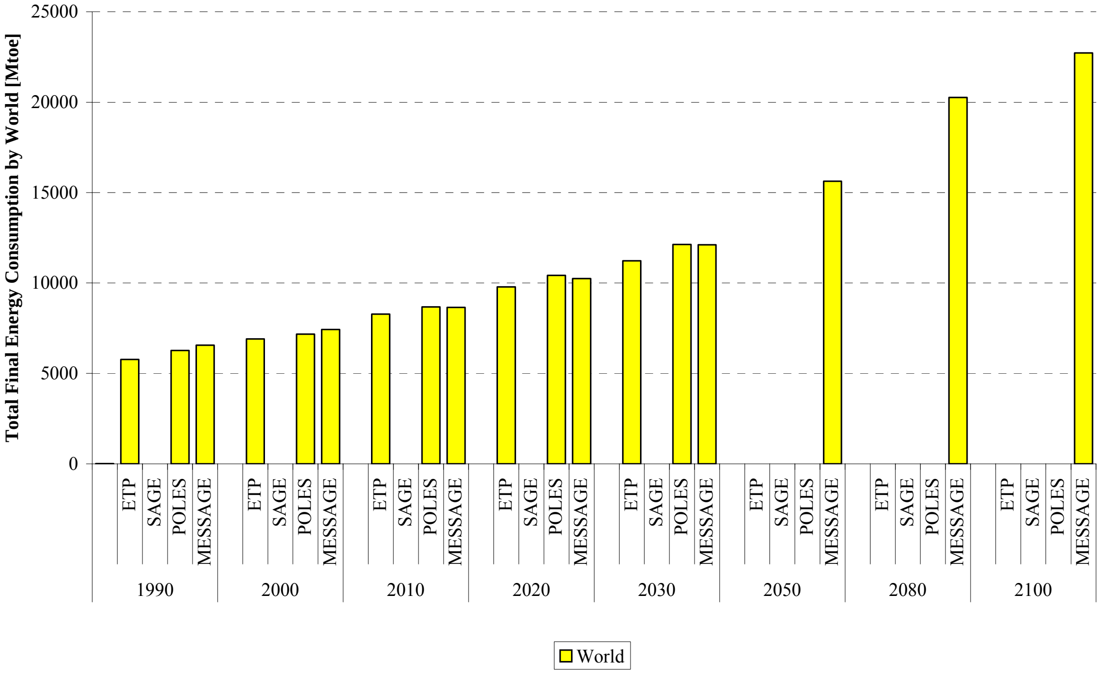

Figure 2-4: World total final energy demand projection by different models

The emission of CO_2 by ETP model remains always in lower side compared to other models, which reflects the higher degree of commercial fuels and non- or low polluting fuels integration inside the demand side. Out of all models, POLES projects the highest emission level in the future periods. The emission of CO_2 by models is presented in the Figure 2-5.

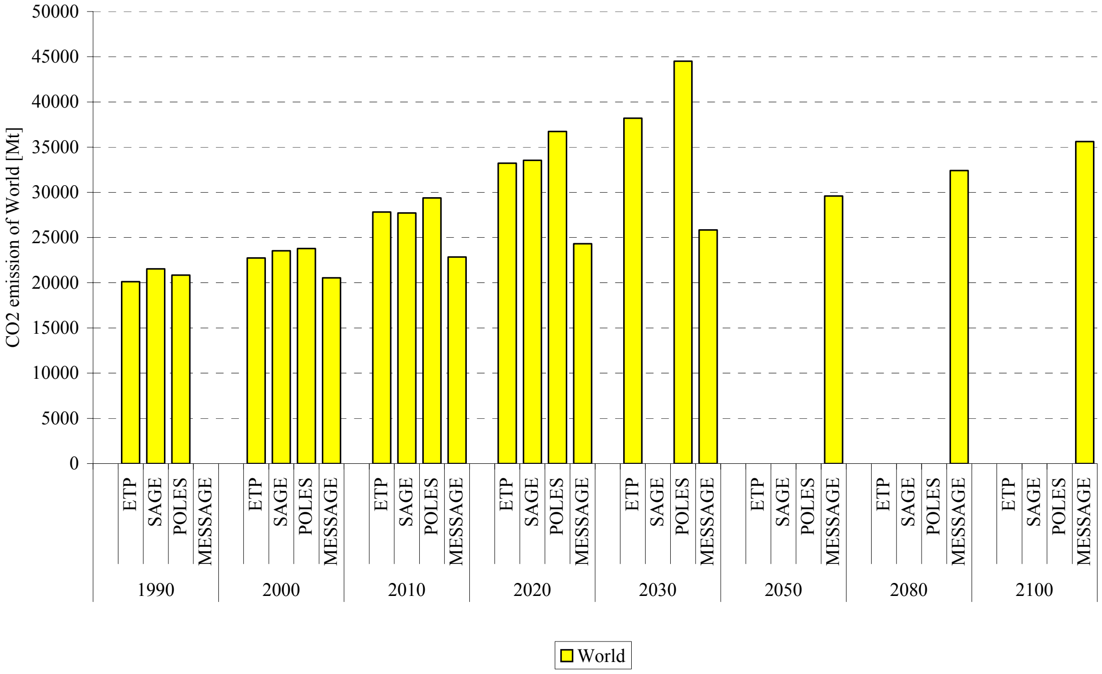

Figure 2-5: World CO_2 emission projection by different models

The value on primary energy, total final energy and CO_2 emission by models for whole world has been provided in this sub-section for the comparison with the present study.

3 Learning Background

The process of learning is a mental and psychological phenomenon, which is natural, spontaneous and may be reflected as improvement of performance in terms of time, cost and knowledge /Barreto 2001/. The reduction of cost and time with respect to increase in production quantity is termed as learning effect in management science /Neij et al. 2000/ and its positive effect is realised by the improvement of knowledge (tacit), experience (skill) and performance. It has been reported in the literature that accumulation of experience reduces the cost of any technology and improves the technological parameters and derives the functional relationship between cost and quantity /Wright 1936/.

The dynamics of technological development originates from the socio-economic interaction, where the learning process play an important role in the change of technological landscape /Barreto 2001/. Since learning is a gradual process, it reinforces its amplitude like a positive feedback in a control system. In other words it can be explained as learning from its own learning, i.e., compound learning, similar to compound interest that represents interest on the interest of a capital. The dynamics of technology is handled exogenously in energy optimisation model by providing through the alternative way of market shares or user constratins.

The technological change is not autonomous and spontaneous, rather it is endogenous to the social system and is a gradual process linked with future opportunities coagulated with existing innovation /Barreto 2001/, the incentives for exploitation, the strength of the institutional and organizational players to carry out the process /Dosi 1997/, though the risk and uncertainty in the return process may be afflicted with the innovation, which is unforeseen during the respective time.

A technology passes through different stages of evolution and development for its competence and existence in the society. Typically, it goes through several stages, from the initial invention (first demonstration stage of feasibility), to innovation (practical application) and finally diffusion (spreading and assimilation of the innovation) /Barreto 2001/. In diffusion state the probability of penetration rate is high inside the society, if the technology is attractive for specific advantages or particular application /Barreto 2001/, but all innovations do not reach the diffusion stage /Nakicenovic 1997/. Still it is uncertain, whether the technology sticks to the society or reaches a niche market, because of the fast technological innovation, though it is fundamentally arduous to predict the future technological path.

When diffusion begins in the niche markets, the feedback from the users helps the firms, other manufacturers, interested actors and policy makers /Kemp 1997a/. However, successful commercialisation depends on further performance improvements and cost reductions that ensure competitiveness. The technology evolves inside the society and matures within the market segments, until new and, possibly better products arrive, which then declines the original products, market penetration and ultimately dies down /Grübler et al. 1999/.

A series of factors affect the dynamics of a technological change, such as the cost and efficiency, market diffusion rate and potential, the influence of R&D expenditure, the inertia and capacity of change of the system /Barreto 2001/. Shaping of technological trajectories to a larger extent depends on environmental impacts, resource availability, efficiency, specific cost, technical skill, market demand and future sustainability. A transition to an environmental compatible energy system will likely to shift the future structure of technological regime /Kemp 1997a/.

Environmentally benign energy system requires the environmentally sound technologies, which can be pioneered by support of research and development in term of demonstration and prototype modules with capability of cost competitiveness with respect to existing conventional technologies. The transition towards a sustainable, clean and emission free energy system could be realised by the early introduction of the new, efficient, advanced and emerging climate friendly technologies. This is in turn, call for methods of analysing the dynamics of energy systems as they pertain to technical innovations and policy instruments for affecting and accelerating a technological change paradigm. Experience curve may provide a tool for analysing this technical shift and policy measures, for implementing and promoting technical dynamics but in general, experience curves are used to analyse the trend of cost reduction of technologies /Neij et al. 2000/. So the learning curve is complex in nature having learning loops around it, both in information feed forward and backward manner /OECD/IEA 2004/.

Future technological path is complex and uncertain, also it is hard to predict as the immense uncertainty present in the innovation track. The process of innovation is itself a mystery and composite phenomenon follows an unpredictable path towards the future. The assessment of environmental healthy technologies in future energy mix is a hard task to forebode as number of technical, environmental, economical and social factors are interacting with each others but understanding such complex dynamics requires necessary policy in future energy market /Kemp 1997a/.

Many sources conduce in the process of cost reduction, those are, change in production and product (process incremental innovations, learning effects and scaling effects); product redesign and standardisation; and change in input to the process /Neij et al. 2000/. The cost reduction, and the experience gained, depends on the market demand, its market potential and possible enlargement. Market demand, in turn, depends on the cost and performance (e.g., quality, function, user-friendliness, efficiency and durability) of the new technology relative to existing technologies. Policy instruments that stimulate technology development and market demand can affect cost reduction, and the rate of cost reduction. Thus the learning process depends on the policy instrument, which enforces the present capacity deployment (penetration rate inside the market) and also the future (reflects the market potential), those are two basic mechanisms for the market oriented technologies /Neij et al. 2000/.

The creation of network for diffusion of innovation /Grübler 1996/; international co-operation to promote clean and efficient energy technologies /Koch 1999/; globalisation of the energy markets /Kydes 1999/ are the main promoters of global learning. Global learning also comes to picture, as the spillover of the learning technology takes place from one region to another /Schaeffer et al. 2004/ by technology and goods /Watanabe et al. 2000/, and the international operation of manufacturing units by multinational companies /OECD/IEA 2000/. The positive effect of learning spillover is, it generates both internal (learning by doing) and external (learning spill-over) economy /Irwin, Klenow 1994/ and the receiver region benefits from forerunner region by technology and learning investment /Schaeffer et al. 2004/.

Global learning can be termed, as the regional cluster, in which a single technology adds its capacity from all regions of world to learn together. Also it can be represented as the global single producer, who produces the same technology for all regions to utilise. The combination of the learning systems can be mapped by the help of learning spillover to form a global learning /Schaeffer et al. 2004/, in which capacity transfer plays a key role.

According to /Gielen et al. 2004/, the technology transfer is termed as the spillover effect of the technology, where the capacity transfer is the key player of the knowledge spillover. So spillover effect can be treated as the technology transfer from one region to another in which the time lag plays an important role. The technology developed in one region will merge in the energy system of another region after some time gap, which involves the commercialization or maturation time taken for the technology. Delaying in the technology has certain extend effect to the production and consumption in different regions /Barreto 2001/

The parameters associated with the technology or a process in exogenous model, changes with sequence of time, as given inside the database and the optimization does not demonstrate the advantage accompanied with early investment. So endogenous modeling of technological learning in the clairvoyant model (having perfect foresight to the future) can prefigure the advantage associated with the technology by early investment. Endogenisation of learning curve inside the long-term energy optimization model has several advantages compared to exogenous models, namely, on system consistency, decision making as well as it provides quantitatively new insights about the penetration of the technology into future energy market, benefit, scope and opportunities affiliated inside the technology.

3.1 State of the art on learning curve

Learning is a cognitive process of acquiring knowledge or skill by a learner, those have the capacity to learn and its practical application upon the object changes the behavior of the parameters such as: cost, time, performance, etc. The learning curve in learning theory, presents an empirical relation between the parameters, but the learning curve in technological context constitute the relation between the investment cost and cumulative experience, quantifying the technological development /Mattsson 1998/, where cumulative experience is acquired by production, installation and process of probing. Endogenous learning is a useful tool for modeling experiments. The highest degree of the development on learning curve until now, its basic ideas, philosophy and application are presented in this document. The upcoming section will explain some of the mathematical equations on singe factor learning, single factor learning with cluster approach, two factor learning and the method followed to include the learning phenomenon inside the objective function of the linearised energy optimization model.

3.1.1 Mathematical equation of single factor learning curve (1FLC)

Single factor learning correlates the investment cost of a technology and cumulative capacity of that technology developed and installed, by stating that the specific cost of a technology reduces with respect to knowledge accumulation, where cumulative capacity deployment is considered as a proxy for the knowledge accumulation. In such as approach a quantitative relationship is drawn between the investment cost and cumulative capacity production and utilisation. Therefore, by generating a graphical representation between cumulative capacity and specific investment cost, a mathematical relation can be established between them. Such an approach has been established in /Barreto 2001/, which can be expressed as,

$$INVCOST_{r,te,t} = a * C_{r,te,t}^{-b} , \qquad \text{Equation 1}$$

and

$$C_{r,te,t} = C_{r,te,(t-1)} + \sum_{j=1}^{T} VAR\_INV_{r,te,j} , \qquad \text{Equation 2}$$

where,

a is the unit specific cost of the technology,

b is learning index of the technology,

r is the region index,

$C_{r,te,t}$ is cumulative capacity of technology te in time period t,

$INVCOST_{te,t}$ is investment cost of the technology (specific cost) te in time period t, and

$VAR\_INV_{r,te,t}$ is investment on the technology te in time period t.

For a given technology 'te', the value 'a' represent the investment cost at unit cumulative production and consumption. The parameter 'b' says about the speed of learning[1] on investment cost with respect to the growth of experience. This parameter 'b' also formulates the progress ratio from where learning rate of the technology can be calculated. For example, if the progress ratio is defined as 0.8 then it implies that by doubling its cumulative capacity, the investment cost of a specific technology will reduces by 20% from its previous value. Similarly, one can define the progress ratio by tripling or quadrupling the cumulative capacity, which means, by each tripling or quadrupling the cumulative capacity of the technology will reduce the specific cost a certain percentage of the previous value. The parameter 'b' is a highly sensible factor inside the learning phenomenon compared to other parameters, and therefore one should be cautious while deriving the progress ratio from an available dataset.

The total cumulative investment cost of single factor learning curve is optimized by inserting it inside the objective function of an energy optimization model, in which total cost optimization to provide the lowest cost energy is the basic criteria. Though total cumulative investment is non-linear and non-convex function, Mixed Integer Programming approach (MIP) has been implemented to linearise the function to include inside the objective function. By using a non linear equation inside the objective function of linear programming TIMES model, can lead to a local optima solution, which can be a local solution thereby not yielding a truly optimal solution. Currently, there is no systematic methodology available to confirm whether a achieved solution local or global optima. The equation representing the total cumulative investment cost that is added inside the objective function could be expressed as:

$$TC_{r,te,t} = \int_0^{C_{te}} a \cdot C_{r,te,t}^{\ -b} * dC = \frac{a}{(1-b)} \cdot C_{r,te,t}^{\ (-b+1)}, \qquad \text{Equation 3}$$

where,

a is the unit specific cost of the technology,

b is learning index of the technology,

$C_{te,t}$ is cumulative capacity of technology te in time period t, and

$TC_{te,t}$ is total cumulative investment cost of the technology te in time period t.

The total cumulative cost expressed in Equation (3) is non-linear and non-convex, which is linearised by MIP approach and implemented in TIMES by piecewise linear approximation as given in Figure 3-1 /Loulou et al. 2005/. Binary variables are defined to control the active segments during the optimization and logical conditions are defined to reduce the optimization time. In piecewise linear segmentation, the choice of number of steps

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[1] Progress Ratio (PR) is defined by the following relationship: $pr = 2^{-b}$

Hence, ***1-pr*** is the cost reduction incurred when cumulative investment is doubled. The value of pr can be defined by 3^{-b}, 4^{-b} etc. and will give same rate of return like 2^{-b} as the rate of return per unit increment in cumulative capacity remains constant.

and their respective lengths are carefully taken to provide a good approximation of the cumulative cost curve. The length of the steps should be small within the rapid change zone of the curve (initial point) and would be greater in the smooth change zone of the curve (final stage). The weighting factor allocated to various approximation steps is as presented in the Equation (4).

$$WEIG(te,i) = \frac{2^{-(KP-i)}}{\sum_{i=0}^{KP-1} 2^{-(KP-i)}}, \qquad \text{Equation 4}$$

where,
KP is the number of segments,
te is for the technology ‘te’, and
i is number of segments and is equal to $\{0,1,2,\ldots,(KP\text{-}1)\}$.

The graphical procedure of four segmentation of total cumulative cost curve, by taking the weighting factor has been shown in Figure 3-1. The value of the TC_0 and TC_{max} refers to the initial and maximum value of total cumulative investment, which reflects the initial cumulative capacity (the technology attains during the starting period of the model) and probably maximum cumulative capacity the technology can attain.

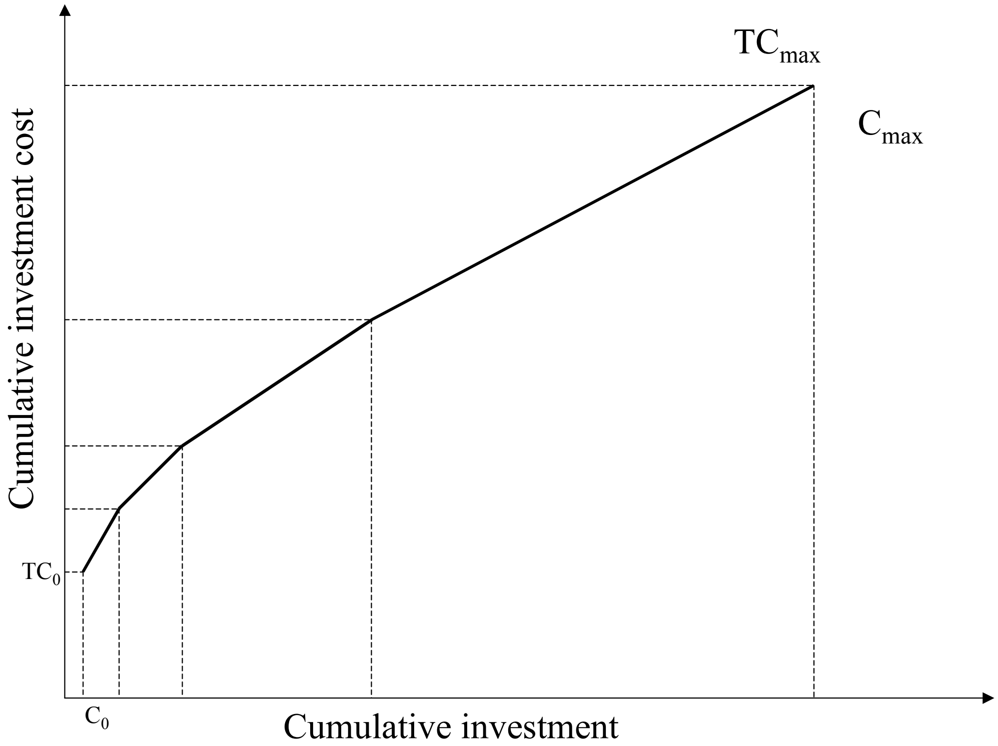

Figure 3-1: Example of a four-segment approximation of the cumulative cost curve

Initial cumulative capacity, maximum cumulative capacity, unit specific cost and progress ratio are the basic parameters of the single factor learning. Therefore derivation of these parameters out of the historical dataset should be ascertained well, especially for the progress ratio, which has the most influential characteristics on learning theory and model result. With same environmental condition of a learning curve, if the learning rate increases, then specific cost of each segment decreases, which has better chance to be selected by the energy optimization model, as the lower cost is the criteria of the model. The lower progress ratio drastically reduces the specific cost, which has higher impact on the technology selection by the model. Not only the progress ratio influences the model result but also the number of segments, initial specific cost, initial and maximum cumulative capacity has significant effect on the decision of the model. Number of segments also controls the specific cost of the technology and affects the model result.

3.1.2 Cluster approach on single factor learning curve

The 'decomposing-clustering' approach developed at Energy Research Centre of the Netherlands (ECN) enables to investigate technological learning for a large number of technologies /de Feber et al. 2002/. The cluster approach is confined to single factor learning domain, where a group of technologies sharing a common component learn together, which are termed as the key technology. The technologies constituting a cluster are related by multiple links that contribute to magnify their economic, social and environmental impacts (Grübler, 1996). These multiple relations contribute to the progress in one of them relevant, directly or indirectly, to other members of the cluster, as it helps to reinforce their own position in the marketplace. An example of a key technology is fuel cell and members of the corresponding cluster of parent technologies are integrated coal gasification fuel cell power plant, combined cycle fuel cell power plant, fuel cell car, etc. Also one technology can appear in more than one cluster, e.g., an integrated coal gasification technology is composed of key technologies like a Gas Turbine (GT), a Steam Turbine (ST), a Gasifier (GF) and a Boiler (BO) /Seebregts et al. 2000/. Each key technology has certain relation with the parent technology towards the cost and capacity development. Thus the allocation of cost and capacity towards learning curve formulation for the key technology requires certain factor in common with parent technology. This common factor is named as the "coupling factor", which essentially relates the parent and key technology in certain proportion. The coupling factor is defined on the level of utilisation of each key technology per unit output of the parent technology.

Coupling factor, defined between a parent and key technology, is required for the non-learning part of cost calculation for parent technology and capacity allocation to key technology. The original mathematical equations used in ECN study and formulated in different way with TIMES notation.

$$C_{r,key,t} = C_{r,key,(t-1)} + NCAP_{r,key,t} \, , \qquad \text{Equation 5}$$

$$CAP_{r,key,t} = \sum_{te=1}^{N} CAP_{r,te,t} * CP\_FT(rte, key) \text{,} \qquad \text{Equation 6}$$

and,

$$INVCOST_{r,key,t} = \sum_{te=1}^{N} INVCOST_{r,te,t} * CP\_FT(r, te, key) \text{,} \qquad \text{Equation 7}$$

where,

$CAP_{r,te,t}$ is the capacity of technology te in time period t,

key is for the technology ‘key’,

te is the parent technology from which key technology originates,

CP_FT (r,te, key) is coupling factor between parent and key technology,

$C_{r,key,t}$ is cumulative capacity of key technology ‘key’ in time period t, and

$NCAP_{r,key,t}$ is new capacity of key technology ‘key’ in time period t.

The capacity allocated to the learning part of the key technology is the sum of all products of parent technology capacity and their corresponding coupling factor. Similarly the non-learning part of the cost is calculated as the difference of the parent technology cost and cost of key technologies multiplied by their respective coupling factors.

$$NCOST_{r,te,t} = INVCOST_{r,te,t} - \sum_{key=1}^{N} INVCOST_{r,key,t} * CP\_FT(r, te, key) \text{,} \qquad \text{Equation 8}$$

where,

$NCOST_{r,te,t}$ is the non-learning cost of parent technology te,

$INVCOST_{r,te,t}$ is the investment cost of parent technology te, and

$INVCOST_{r,key,t}$ is the investment cost of key technology key.

The capital cost of a technology in the cluster is decomposed into two parts. One part is associated with the key technology that learns and other part is non-learning part of the parent technology. One can easily calculate this non-learning part of cost from Equation (8) as presented in the earlier text. The non-learning part of the cost is given inside the database exogenously for each technology during the running of the cluster approach methodology.

The single factor cluster approach had many advantages over single factor learning such as: reduction of number of learning curves, sets, parameters, variables, equations, optimization time and utilization of the memory size. In this cluster approach the availability factor of the key technology is set to zero to reflect that the key technology will not produce any output rather the parent technology that sums up the key technology capacity inside it and avoid double counting of this parameter inside the model.

3.1.3 Learning spillover

The learning accumulated in one technology may spill to trigger improvements in other technologies; or the performance or cost advances in one of them makes a whole chain of related technologies more attractive than an alternative system. Learning not only spills from one technology to another for its betterment but also it spills from one region to another for the cost reduction as well as performance improvement.

The multi-regional learning is, the learning in between the forerunner and entrant countries upon the same technology. One region is completely developed in technological viewpoint and the other is in the rudimentary phase. The experience curve on any technology, a nation or region starts at a much lower price level than another country, if the market begins to develop later. For an example, the experience curves on solar PV in which all European countries benefit from the big efforts of Germany, in which the knowledge spilled from Germany to all European countries..

Global learning comes to picture, as the spillover of the learning technology takes place from one to another region both by technology and skilled workers, in which knowledge is transferred through skilled persons from one region to other. The rate of knowledge transfer depends on the level of technological knowledge the donor has and the capacity and infrastructure the receptor to acquire. Therefore the technologically lack regions are benefited both by knowledge and learning investment from technologically lead regions /Schaeffer et al. 2004/.

Inter-regional learning can be considered from the point of manufacturers are inspired by manufacturers, multinational companies, migration of skilled persons from one region to other, R&D expenditures by learning sink regions to attain knowledge from learning source regions, knowledge transfer by personal contacts (like projects, seminars, methodological workshops, presentations, talks etc.), product dissemination from the boundary of the produced region and free trade of global market policy are reasonable factors for global learning. Countries without domestic manufacturers learn from the manufacturing and deployment of technology by other regions /Neij et al. 2000/.

Environmental condition; market situation, structure and potential has impingement on the learning spillover, for example Japan is in the niche market on solar PV, so one region will find cheap to import the technology than going for huge investment on the learning, and thinking in the way around, the company will try to sell as much as the technology produced to recover its learning investment and try to make more profit, irrespective of its regional boundary by taking advantage of free global trade market. Other factors like joint venture on certain technology by different regions e.g., India and Spain in wind power; USA, China and European union in fusion power will influence global learning. Global learning is further cited by the leading role of multinational companies operated internationally and has manufacturing units in various regions.

Under a new paradigm characterized by a dramatic increase in the transboundary flow of people, goods and information together with an increase in technology complementarity through capital stock and labour forces has accelerated the growth and spread of global technology spillover /Watanabe et al. 2000/.

Spillover coefficient coming, from the capacity transfer, could be accounted only in the multi-regional model, where each region may learn by itself or globally. In individual region within multi regional sphere, the technology installed in one region will add to the cumulative capacity of other regions to reduce the specific cost of the technology in that region but in global learning the installation of capacity in all regions add together and learn to decrease the specific cost. This phenomenon can be explained as single producer to supply the technology to different locations collectively. The original mathematical equation on spillover is taken from the work of /Barreto 2001/ and presented beneath.

$$C_{te,i,t} = C_{te,i,0} + \sum_{\tau=1}^{T}\sum_{j=1}^{N} \sigma_{i,j,\tau} * VAR\_INV_{te,j,\tau} \,, \qquad \text{Equation 9}$$

where,
te is for technology ‘te’,
i, j are regional index i, j $\in$ {1, …,N},
t, ζ are time indexes,
$C_{te,i,0}$ is the initial cumulative capacity of technology te in the region i,
$VAR\_INV_{te,j,t}$ is the investment on technology te in the region j for the period t, and
$\delta_{i,j,t}$ is spill-over coefficient between region i and j for the period t.

The $\delta_{i,j,t}$ (0,1) is the spillover coefficient and represents the fraction of the installations made in region j, added to cumulative capacity in region i, to compute investment cost in the period t.

3.1.4 Two factor learning curve (2FLC)

In single factor learning curve, only cumulative capacity is represented as the parameter to accumulate the knowledge for which the specific cost of the technology reduces. But in reality it is not only the cumulative capacity, which is responsible for the technological knowledge development, rather many factors have influence on it; learning by doing (production process, know-how), learning by searching (R&D expenditure, know-why), learning by using (utilisation of the technology, know-what), learning by interacting (transfer of knowledge between users, producers, research institutes and policy makers) /Kamp 2002/, learning by learning (reflexive or second order learning, indicating self reinforcement of learning) /Rotmans et al. 2003/ and learning by expanding (more application and more participation from actors and organisations) /Schaeffer et al. 2004/.

Out of many factors influencing on the reduction of investment cost of a technology, cumulative capacity and R&D expenditure are two main factors. To realise and understand the influence of R&D expenditure on specific cost of the immature technologies draws immense attraction from last decade. It gains interest from all sides starting from developers, investors and researchers to trace the influence of R&D expenditure, specifically on new technologies /Barreto 2001/.

R&D expenditure is an important factor in the cost reduction and performance improvement of the technology in the early stage of development. Before commercialisation of the technology, it is R&D expenditure, which only reduces the specific cost of the technology but after market penetration of the technology, production process, market mechanism and government policy regulates the reduction of investment cost, subsequently the R&D expenditure more or less goes towards the technological development like improvement of efficiency, availability factor, reliability, material quality, strategy for emission reduction and technical life time /Barreto 2001/.

Public R&D support for a technology or family of technologies usually extends over several years, as the return from the R&D is always higher than the return from the capacity deployment /Griliches 1995/, /Klaassen at al. 2003/ and /Barreto 2001/, but it is hard to measure the payoff. Without any R&D expenditure it may increase the investment costs of the technology /Barreto 2001/. So there should be continuous R&D expenditure on technologies to keep all parameters coherent, but sometimes the stopping of the R&D support may be the reason for too slow progress of the technology or technology reached at maturity stage and further development should be left to the market development /OECD/IEA 2000/. The rate of depreciation and time lag have been defined on knowledge stock in which the depreciation rate is an important element of “forgetting-by-not-doing” that is introduced in the R&D component of the learning process. The study by /Klaassen et al. 2003/ on wind turbine of Denmark, Germany and United Kingdom found the lbd rate of 5.4% and lbs rate of 12.6%, by interpreting the return from the R&D investment is high compared to capacity deployment.

3.1.5 Two factor learning approach by ERIS (1)

In this approach the R&D expenditure is considered as a factor for the development of the knowledge, which is responsible for the reduction of the specific cost of a technology. So the specific cost of a technology is expressed as the function of cumulative capacity and cumulative R&D expenditure.

$$INVCOST_{r,te,t} = a * C_{r,te,t}^{-b} * CR\&D_{r,te,t}^{-c}, \qquad \text{Equation 10}$$

and,

$$TC_{r,te,t} = \int_0^{C_{te}} a \cdot C_{r,te,t}^{\ \ -b} * CR\,\&\,D_{r,te,t} * dC = \frac{a}{(1-b)} \cdot C_{r,te,t}^{\ \ (-b+1)} * C\,\&\,RD_{r,te,t}^{-c}\ , \quad \text{Equation 11}$$

where,

$C_{r,te,t}$ is cumulative capacity of the technology te,

$CR\&D_{r,te,t}$ is cumulative R&D expenditure of the technology te in monetary unit,

b is the learning by doing & learning by using index (lbd&lbu),

c is the learning by searching index (lbs), and

a is the specific cost at unit cumulative capacity and unit cumulative R&D expenditure.

The term $C\,\&\,RD_{r,te,t}^{-c}$ in the Equation (11) does not ensure the non-decreasing value of the total cumulative cost. So the investment cost in-between two periods may take negative value, if the R&D expenditure produces too steep decrease of the specific cost of the technology. Also this approach does not provide hints upon the obsolescence and depreciation of the knowledge. The objective function of the total cumulative cost is contributed by cumulative capacity and cumulative R&D expenditure and both parameters contribute in the same monetary unit. However the contribution by each entity could not be analysed separately, as one unit of both entities produces the same effect /Barreto et al. 2002/.

In this approach, it is assumed that the R&D expenditure gives immediate effect and also the knowledge does not depreciate or obsolete. But in practical situation, it is not possible. So taking those two factors into account ERIS has formulated knowledge stock approach, which is interpreted below.

3.1.6 Two factor learning approach by ERIS (2)

In this approach the R&D expenditure is represented in the form of knowledge stock formulation /Watanabe 1995&1999/. The knowledge stock development considers the depreciation of the knowledge with respect to time, the time lag between the R&D expenditure and implementation of the knowledge developed in practical field or product manufacturing.

$$INVCOST_{r,te,t} = a * C_{r,te,t}^{-b} * KS_{r,te,t}^{-c}\ , \quad \text{Equation 12}$$

$$KS_{r,te,t} = (1-\sigma) KS_{r,te,(t-1)} + R\,\&\,D_{r,te,(t-x)}\ , \quad \text{Equation 13}$$

and

$$TC_{r,te,t} = \int_0^{C_{te}} a \cdot C_{r,te,t}^{\ \ -b} * KS_{r,te,t} * dC = \frac{a}{(1-b)} \cdot C_{r,te,t}^{\ \ (-b+1)} * KS_{r,te,t}^{-c}\ , \quad \text{Equation 14}$$

where,

$KS_{r,te,t}$ is the knowledge stock in the year t for technology te in monetary unit,

δ is the depreciation rate for knowledge stock, and x is the time lag between the R&D expenditure and commercialisation of the product.

Continuous R&D expenditure is required in this approach to compensate the knowledge depreciation. Without continuous R&D expenditure, the knowledge stock may decline by the introduction of depreciation rate and figure out the investment cost as negative value in between two periods. So the consideration of time lag and depreciation rate has significant influence on the selection of future technologies.

Various authors propose different values of the depreciation and time lag factor in their studies. The study of /Watanabe et al. 2000(2)/ used the time lag between R&D expenditure and the knowledge implementation as 2.8 years and depreciation rate of 20.3% (inverse of technical life time of the technology). Likewise study of /Barreto 2001/ has considered the time lag of 4 years and depreciation rate variation from 0-15%. Suggestion from /Griliches 1998/ for time lag in commercial R&D expenditure as 2-5 years and depreciation rate of 10%. Crique has considered 3% depreciation rate /IEPE 2001/ and work by /Klaassen et al. 2003/ proposed 2-3 years time lag and 3% depreciation rate.

3.1.7 Two factor learning approach by ECN

The ECN has followed an indirect approach in two-factor learning curve formulation in which the public R&D expenditure goes towards the development of the progress ratio. So the net progress ratio will be contributed by both cumulative capacity deployment and the public R&D expenditure /de Feber et al. 2003/. In this approach ECN has assumed the public R&D expenditure as a good indicator of the overall R&D expenditure and the additional R&D budget (an ‘R&D shock’) will lead to an increase in R&D intensity of the technology. The relation between the R&D intensity and the R&D expenditure is given in the Equation (15). The higher is the R&D intensity, better is the progress ratio, i.e., the increase of R&D intensity reduces the progress ratio and increases the learning rate of the technology. Therefore the specific cost or investment cost of the technology reduces by the R&D expenditure. The additional R&D implies the extra R&D expenditure over the minimal R&D expenses in the base case. The other assumptions taken are the relationship between the R&D intensity and change in PR is same for all technologies and the progress ratio will not change after the period of additional R&D shock. The quantitative relation between R&D intensity and change in progress ratio has been fitted on available statistics and taken from the work of /Kram et al. 2000/ and /Criqui 2001/.

$$R\&DI_{r,te,t} = (R\&D)/(R\&D + turnover), \qquad \text{Equation 15}$$

and,

$$PR = -0.29*(R\&DI_{r,te,t}) + 0.9451(R^2 = 0.9898), \qquad \text{Equation 16}$$

where,

$R\&DI_{te,t}$ is the R&D intensity of the technology te in time period t,

R&D of the research and development expenditure,
PR is the progress ratio,
‘turnover’ is the amount of expenditure towards the human development, and
R^2 is correlation coefficient coming from least square method.

3.1.8 MILP approach on two factor learning curve by IER

The idea behind the two-factor learning curve is, the R&D expenditure will be responsible for the specific cost reduction and can be understood easily from the given Figure 3-2. The graph demonstrates the method of the specific cost reduction by R&D expenditure strikes to the generic learning curve. So the R&D expenditure spend in the demonstration phase of any technology reduces the specific cost. In this approach the specific cost reduction by cumulative capacity deployment is taken as the correlation between the cost and cumulative capacity to find out the progress ratio. Alike single factor learning, the progress ratio by the R&D expenditure has been calculated by regression analysis between the investment cost and cumulative R&D expenditure. In this work the stepwise reduction of specific investment cost was realised based on the structure of R&D expenditure. In analogue, the R&D expenditure goes for the production of fictive capacity, which does not add any value to the real cumulative capacity. The total cost (cumulative R&D expenditure and total cost from cumulative capacity), in relation to cumulative capacity (real and fictive) is given in Figure 3-3.

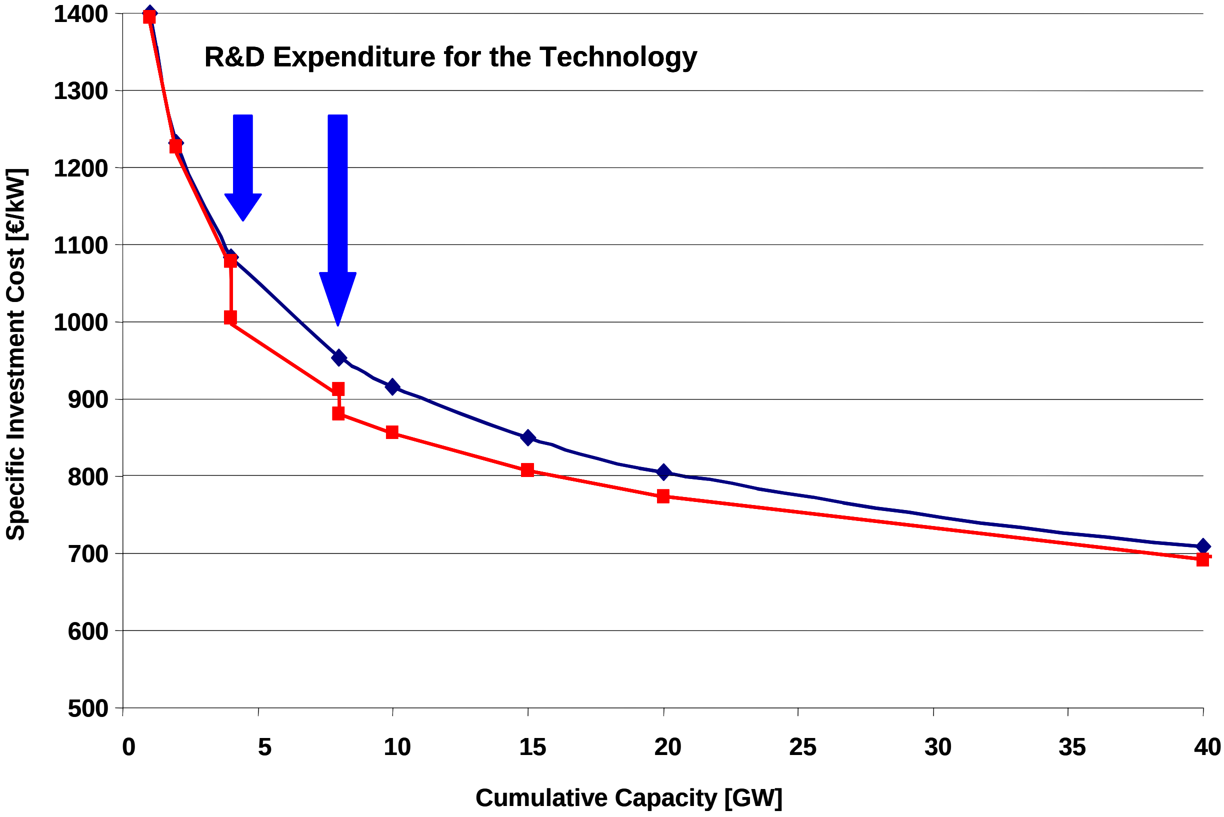

Figure 3-2: Impact of R&D expenditure on specific investment cost of any technology

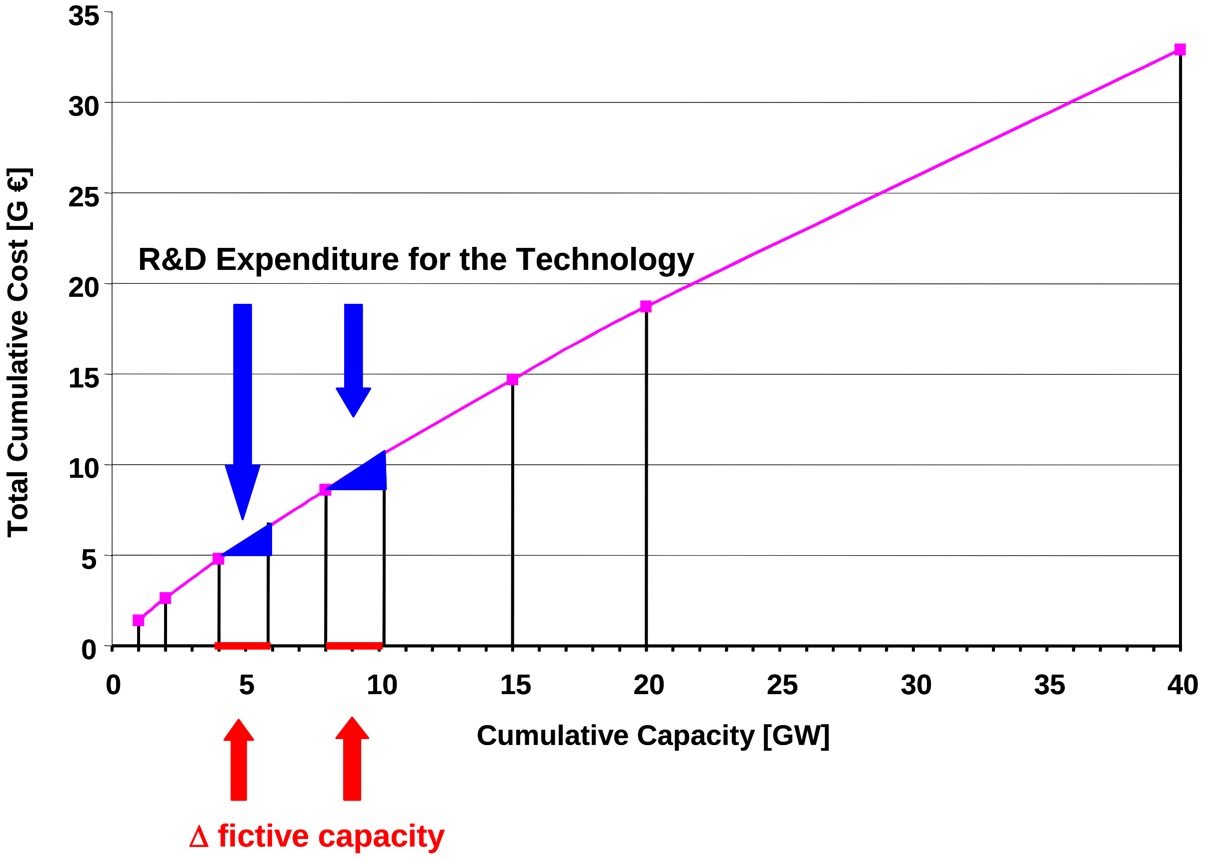

Figure 3-3: Impact of R&D expenditure on total cumulative cost of any technology

Analogous to single factor learning, total cost (investment and R&D) in two-factor learning is non-linear. So separable programming is considered for the approximation of total cost curve. The non-convexity of the cost function is approximated by piecewise linear approximation and binary variables are introduced to handle some logical conditions to minimise the optimisation time and to get the global optimum solution.

$$TC_{r,te,t} = \sum_{i=1}^{N} \alpha_{i,te} \cdot \delta_{te,i,t} + \beta_{i,te} \cdot \lambda_{te,i,t} \,, \qquad \text{Equation 17}$$

Corresponding to the total capacity, which is the summation of real capacity installation and the fictive capacity coming from R&D expenditure is written in the mathematical form.

$$C_{r,te,t} = C_{r,te,0} + \sum_{\tau=1}^{t} ncap_{r,te,\tau} + \sum_{\tau=1}^{t} ncap\_R\&D_{r,te,\tau} = \sum_{i=1}^{N} \lambda_{te,i,t} \,, \qquad \text{Equation 18}$$

and the logical condition for convexification can be written as,

$$\sum_{i=1}^{N} \delta_{te,i,t} = 1 \,, \qquad \text{Equation 19}$$

and

$$\begin{aligned} \lambda_{te,i,t} &\geq C_{i,te} \cdot \delta_{te,i,t} \\ \lambda_{te,i,t} &\leq C_{i+1,te} \cdot \delta_{te,i,t} \end{aligned} \,, \qquad \text{Equation 20}$$

The amount of fictive capacity development depends on the quantity of the R&D expenditure allocated towards the individual technology or technologies as a whole. If the R&D expenditure will always induces constant fictive capacity then there will be linear relation between fictive capacity and R&D expenditure. This implies that the efficiency of R&D expenditure with respect to cumulative capacity decreases, and this value may decline compared to future demonstration projects. The assumption taken here is the efficiency of R&D expenditure concerning the learning rate of any technology remains constant. The separable optimisation under piecewise binary convexification has been adopted here for describing the mathematical equations.

$$C_{r,te,t-1} + \sum_{\tau=1}^{t} ncap\_R\&D_{r,te,\tau} = \sum_{i=1}^{N} \lambda R_{te,i,t} \,, \qquad \text{Equation 21}$$

Total cumulative R&D expenditure will be written as:

$$TCR_{r,te,t} = \sum_{i=1}^{N} \alpha_{i,te} \cdot \delta R_{te,i,t} + \beta_{i,te} \cdot \lambda R_{i,te,t} \,, \qquad \text{Equation 22}$$

Logical condition for convexification,

$$\begin{aligned} \lambda R_{te,i,t} &\geq C_{i,te} \cdot \delta R_{te,i,t} \\ \lambda R_{te,i,t} &\leq C_{i+1,te} \cdot \delta R_{te,i,t} \end{aligned} \,, \qquad \text{Equation 23}$$

The R&D expenditure (R&DE$_{te,t}$) for one technology te in model period t is,

$$R\&DE_{r,te,t} = R\&DI_{r,te,t} \cdot TCR_{r,te,t} - TC_{r,te,t-1} \,, \qquad \text{Equation 24}$$

The categorisation of R&D-Intensity for any technology can be expressed as,

$$\mathrm{R\,\&\,D\,I}_{\mathrm{r,te,t}} = \begin{cases} < 1 & \\ 1 & \text{Lerning by doing} \\ > 1 & \end{cases}$$

where,
$C_{r,te,t}$ is the cumulative capacity by lbd,
α if the y-axis intercept of each segment and represents the total cumulative cost,
β is the slope of the segment,
δ is binary variable,
δR is binary variable, when R&D expenditure is applied,
λ is continuous variable,
λR is continuous variable, when R&D expenditure is implemented,
$TC_{r,te,t}$ is total cumulative cost of technology te in time period t,
$TCR_{r,te,t}$ is total cumulative cost of technology te in time period t, when R&D expenditure is utilised,
$ncap\_R\&D_{r,te,t}$ is the new capacity by lbs,
$R\&DI_{r,te,t}$ is ($R\&D_{eff}/(R\&D_{eff}$+others)), and
$R\&DE_{r,te,t}$ is the R&D expenditure for technology te in time period t.

The value of R&D intensity can be one, greater than one and less than one. The unit value of the R&D intensity represents the R&D investment only in demonstration project. The R&D expenditure leads to increase of the cumulative capacity and reduces the investment cost. The philosophy behind this learning approach is, the cumulative capacity increases due to demonstration project, following which the learning rate increases and reduces the specific investment cost. The R&D intensity greater than one is desirable for the technology development and cost reduction and less than one can be achievable thought demonstration projects.

The total amount of R&D budget TR&DE can be restricted inside the model by period wise or by model horizon, i.e., total for all periods. The total R&D expenditure is mathematically described in Equation (25).

$$TR\,\&\,DE = \sum_{te=1,\tau=1}^{N,T} R\,\&\,DE_{r,te,\tau}\ , \qquad \text{Equation 25}$$

where,
TR&DE is the total amount of R&D budget, and
$R\&DE_{r,te,t}$ is the R&D expenditure for technology te in time period t.

Total R&D expenditure consists of public and private (industrial) R&D expenditures, where, it is hard to distinguish them. It is also difficult to get the public R&D expenditure for any technology or group of technologies on national, regional and worldwide basis. The public R&D expenditure may be calculated and approximated from numbers of patents, but still it is uncertain.

The investment cost of the technology has influence on the model results. The endogenous development of the investment cost by the MIP approach of learning curve is influenced by the uncertainty on learning rates. Subject to different learning rates, the investment cost development is different and sometimes the investment cost reaches approximately zero value depending on the learning parameter. Therefore, it is required to restrict the development of the investment cost of the learning technologies, i.e., the investment cost will not learn after reaching at a certain value. Also, it is quite essential to implement knowledge lack or technology gap inside global learning on multi regional context as the developing and developed regions have different level of knowledge on the consumption of the same technology, which is reflected on the investment cost of the technology. With passage of time developing and developed regions attain same level of knowledge and see same specific cost of the technology. The knowledge transfer from the developed regions to developing regions arouse interest, how the knowledge spillover takes place and could be handled inside the energy optimization model.

3.1.9 Conclusion and critical view

Conclusion on respective learning approaches is presented below with their merits and further improvement. Single factor learning will be more appropriate on unit capacity basis than technology as a whole. Also the attempt should be taken in the direction of reduction in the gap length between the real total cumulative cost figure and the optimized value of the total cumulative cost, which comes from the linearization of the total cumulative cost curve by fixed charge problem.

There is no quantitative relationship that accurately models learning theory based on knowledge development, to answer the question various questions on how and when, each player is responsible and contributes to the development of the knowledge, which is the sole factor for reduction of the investment cost. When the total reduction of specific cost of a technology plotted against of a single factor (cumulative capacity, cumulative R&D expenditure, etc.) the learning curve fits to the dataset very well. However the rate of payoff is higher when compared to any individual factor as a single cause is evaluated against the cumulative effect. Therefore cost reduction cannot be achieved as a result of a single entity. The role of each factor in the specific cost reduction is not the same at different time and stage of a technological development. Additionally, the process of production and installation does not reduce the specific cost of a technology, rather it is the human brain, which receives the knowledge, and its application reduces the specific cost, which is the (core idea of single factor learning), preferable than deployment of the capacity. Thus, optimization of the total cumulative investment may be considered in a different way.

Single factor learning curve does not quantify the knowledge, which is treated as the cause of a specific cost reduction. Additionally, this approach only defines a theoretical relationship between knowledge and specific cost, and it does not consider how they are correlated quantitatively. Therefore, establishing a quantitative relation between knowledge and the specific cost relation is an interesting and challenging research area.

Selection of the progress ratio for a technology is difficult to decide; as the progress ratio of the nascent and prototype stage of the technology shows lower value compared to old and matured technologies. Thus the consideration of the PR coming from early stage of technology development may not reasonable for that technology in future. Therefore multi progress ratio option could not be omitted for single factor learning.

Any energy system model sees only Learning By Using (lbu) cumulative capacity for knowledge development and Learning By Doing (lbd) capacity development does not come into picture. Therefore the PR should be defined based on lbu rather considering both lbd and lbu, on the other hand the investment cost purely depends on lbd than lbu, where lbu may provide feedback to the lbd. As well any given technology showing learning in the prototype phase may or may not learn in the future. The technology may follow the “lock-out” effect (will not integrate inside the future energy technological mix) before reaching saturation (crisis in the technology, policy and regulation, technological breakthroughs for cost reductions, change in consumer attitude, niche markets and pressure to achieve environmental goal) /Cowan and Hultén 1996/ and some technologies follow the “lock-in” (will integrate inside the future energy technological mix), (increasing return, learning effect, economies of scale, network externalities, technological interrelatedness, information exchange) status to learn in future.

Furthermore, single factor learning does not considered extensively the depreciation and obsolete of the knowledge. Likewise the development of the skill and its implementation has no time lag.

Cluster of technology should focus on the unit capacity value of key technology because this is the deciding factor for the specific cost of the parent technologies. For example, fuel cell used in mobile technology cannot be included inside the same cluster of fuel cell used in power generation. Fuel cell used in mobile is more sophisticated, compact and cost more per unit capacity than the fuel cell used to generate power.

The development of the coupling factor needs special attention. The cost breakdown can lead to negative non-learning part of the cost parameters, as the unit capacity cost of key technology in all parent technologies does not match. The capacity derived for key technology sometimes becomes higher than the parent technologies (coupling factor >1), so the learning curve will follow penny switch effect on those technologies to reduce the cost as soon as possible (by less investment it gets more capacity).

The learning spillover says that the cost reduction in one region takes place by the deployment of capacity in another region. Hence, it can be thought that the production of total capacity in one region spills some part of its products to other region. So the Learning By Doing (lbd) capacity in the production region will be the summation of the Learning By Using (lbu) capacity of all regions, to which it has been transferred.

People expect that due to the combined effect of cumulative capacity and R&D expenditure, the specific cost of the technology will reduce a greater extend by decrease of PR (ECN), which will reduce drastically the investment cost of the technology. But in reality will it be the real case? Any type of single factor learning gives the highest percentage of cost reduction against multifactor learning process, as the combined effect is plotted against the individual cause. So the PR by individual entity in the 2FLC will be higher (higher PR and lower Learning Rate (LR)), which will reflect the lower return in 2FL than the 1FL.

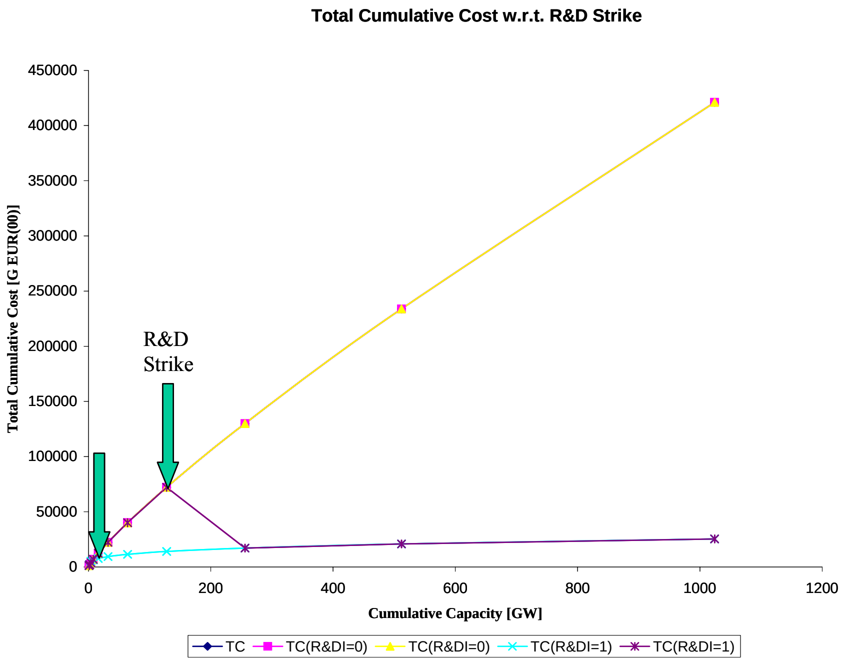

Figure 3-4: Change of total cost with change of PR by R&D strike

In the indirect approach of two-factor learning curve by ECN, it is interesting point, how the total cumulative cost curve formulation takes place, especially when the progress ratio changes and how the optimization subroutine handles the change in progress ratio by MIP approach, if the objective function takes the same total cumulative cost curve as single factor learning. The phase change from one progress ratio to another is quite concerning point.

In this approach, if the same objective function formulation has been considered like single factor learning, then the phase change will be a big matter for optimization subroutine and will produce large error depending on the R&D intensity change level (0 to 1). The error term is minimum for R&D intensity of zero value and will be maximum for R&D intensity of 1. Also it depends on the stage of R&D impact, i.e., if the R&D impacts in the prototype phase of the technology then there will be minimal error in optimization subroutine and if the strikes takes place towards the saturation part of the technology (e.g. when cumulative capacity is high), then there will be big margin error in the optimization and will not provide the real global optima rather follow the non-linear path towards local optima.

Any lineralized approach of two-factor learning curve brings curiosity to the researcher on the formulation of total cumulative cost curve, which is the objective function in learning theory. How and based on which equation it has been formulated, linearised and optimized. The methodology adopted for the calculation of the time lag and the depreciation of knowledge has not been reported in indirect approach of two-factor learning curve.

R&D intensity may or may not produce the same effect to decrease the progress ratio at each and every stage. If R&D expenditure at each and every stage is capable to reduce the specific cost in same proportion, then why one will not spend much R&D on one technology for drastic reduction of specific cost?

Fictive capacity methodology is a good approach on multifaceted learning phenomenon. Both cumulative capacity and R&D expenditure has been inserted in linearised fashion to reflect the activity of specific cost by the influence of both entities. In this case the R&D spending is restricted within the prototype phase of the technology. When the product passes through the prototype phase and entered inside the commercialization stage, then R&D spending has no contribution to the specific cost reduction of the technology and it is left solely on future market.

3.2 Methodology

The methodologies are developed on global learning in context of technology gap or knowledge gap. The knowledge gap or knowledge lack between developed and developing regions are presented in two different approaches to know the technology behaviours subject to uncertainty of learning rates in multi-regional energy system model on global learning concept. Also the methodology on floor cost approach has been developed to handle the uncertainty in learning rates of technologies inside the energy optimization model. In this approach the specific cost of the technology does not fall below a certain level of the initial specific cost. To avoid this problem floor cost approach is required to implement.

3.2.1 Uncertainties with learning rates

Technological progress is uncertain, and is hard to predict the future behaviour of any technology that has the most influence or has no place in the present market. The progress of a technology, in its early stage of development, may not cope with its prototype stage as well as the mature phase /Barreto 2001/. The ability of a given technology to sustain over time is defined by a parameter called progress ratio. Progress ratio is an important parameter in learning theory that depicts the behaviour of investment cost of a technology with accumulation of knowledge. Progress ratio, in learning theory, is complementary of learning rate, which states that the specific cost of a technology is lowered by a certain percentage when its cumulative capacity is doubled. Progress ratio reflects the advancement of technological knowledge with increase in cumulative capacity deployment that is directly related to specific cost of the technology. It is calculated by regression analysis of the logarithmic value of a series of available historical dataset on unit investment cost and corresponding cumulative capacity. These data are possibly supported by expert judgment in many of the cases. But historical data often display errors, interruptions and gaps, which shows unexplainable jumps or missing dataset /van der Zwaanet et al. 2002/. Additionally, they have been obtained through various measurement techniques, which leads to discrepancies in internal consistency. Sometimes the progress ratio is derived from in-genuine dataset coming from unreliable sources.

Actual PR computation of a technology is quite cumbersome, because of the competing industry does not want to disclose their internal secret by apprehension of marketing, as well as the data depends on the company's brand, quality and product. The difference in the progress ratio on same technology varies, as the sources of data is not reliable especially for new, climate friendly and renewable technologies, because of the developer (specially private entrepreneurs) are not interested to disclose their intellectual property (IP) secret, which may negatively impact their business.

Uncertainty on learning rate originates from different corner by the inter linkage of many factors and their uncertainty. Technological change is primary cause of uncertainty on learning rate, which is costly and uncertain. Technological change requires dedicated effort in the form of R&D expenditure /Blesl et al. 2005/, market mechanism /Neij et al. 2000/; and R&D and demonstration project /Grübler and Gritsevskii/ with risk in learning investment. Uncertainty is associated with the economic risks and opportunities; those are main driver of technological evolution and development.

The variation of learning rates of a given technology depends on cumulative capacity and its contemporary investment cost those are difficult to determine on local, regional and global basis. It constitutes the slope in-between the investment cost and cumulative capacity, so the development of cumulative capacity and corresponding specific cost available from sources, matters in calculation of the progress ratio. The stage of a technology from which data is collected to compute learning parameters is vital factor to modeling aspects and the optimization result. The stage of a technology from which the data has been collected does not reflect consistency of a technology in past and in the future. If the technology is in its matured phase then the uncertainty concealed inside the derivation of PR is less. However, if the data collection is from the rudimentary stage of the technology (before reaching prototype stage) then the uncertainty affiliated with the technology is high. In essence, the future technological path is arduous to predict. Therefore, uncertainties are basis blocks of the technological path /Wene 2003/. Also the uncertainty in R&D expenditure towards the development of the new technology is uncertain, in different stage of the technology develpment, which drags for the uncertainty in learning rates /Christiansson 1995/, /Ayres and Martinàs 1992/ and /Grübler et al. 1999/.

The work of /Schrattenholzer 1998a/ illustrates the variability of progress ratio using the example of several energy technologies. Depending on the datasets, time spans and performance indicators (e.g., price instead of cost) being considered, different estimates are obtained. Also, in his analysis, some technologies were shown to experience declining learning rates over time. The work of /Argote and Epple 1990/ reported learning rates for a number of industrial products in the range of 56% to 100%, with an average value of 80%. This clearly indicates the strength of uncertainty associated within learning rates.

Historical estimates provide valuable information but the observed trend may or may not continue in future, as new developments may cause an alteration of the learning trajectory /Barreto 2001/. Thus extrapolation of the progress ratio from the historical trend may be over or underestimated. The model will favor underestimated PR, but the risk of investment could not be recovered, as the unforeseen better technology could be more costly than expected. On the other hand, overestimation of the PR will alter the profit margin and hamper the selling quantity of a company, as the research results has direct influence to the human attitude /Grübler and Gritsevskyi/. Based on these factors, how the model will be influenced by uncertainty of the progress ratios and the variation of the investment cost concerning the variation of progress ratios are provided in the Table 3-1 and Figure 3-5.

Table 3-1: Uncertainty and inconsistency of progress ratios

Technology progress ratio											
Technology	by Sources							by Models			
	/Barreto 2001/	/Cirqui 2000/	/Kram et al. 2000/	/McDonald et al. 2001/	/Junginger 2000/	/Kouvaritakis et al. 2000(a,b)/	/Messner 1997/	MARKAL (europe model)	MARKAL (global model)	MESSAGE (gobal model)	ERIS (global model)
Advanced Coal	0.94					0.89	0.93		0.94	0.93	0.95
Fuel cell			0.66				0.85	0.9	0.87		0.82
Gas Combined Cycle	0.9					0.76	0.85		0.89	0.85	0.88
Gas Fuel Cell	0.82					0.81					
New Nuclear	0.96					0.96	0.93	0.82	0.96	0.93	
Solar PV	0.81	0.8	0.72-0.85	0.8		0.75	0.72		0.81	0.72	0.85
Wind Power	0.9	0.83	0.85-0.9	0.83-0.92	0.85-0.96	0.84	0.85	0.81	0.89	0.85	0.88

From the Table 3-1 and Figure 3-5, it can be derived that the process of data collection and calculation of progress ratios differs in such a way that the value of progress ratio on same technology has large disparities among researchers. Also the data collection on sector-wise, regional and global basis has significant effect on the progress ratio calculation and variation in assumptions of the progress ratio influences on the model result, which can be visualized from the Figure 3-5. Though all the technologies seem to start nearly at the same point but towards the end point they have wide variation in their specific cost. Not only the progress ratio influences the model result but also the number of segments, initial specific cost, initial and maximum cumulative capacity has significant effect on the decision of the model.

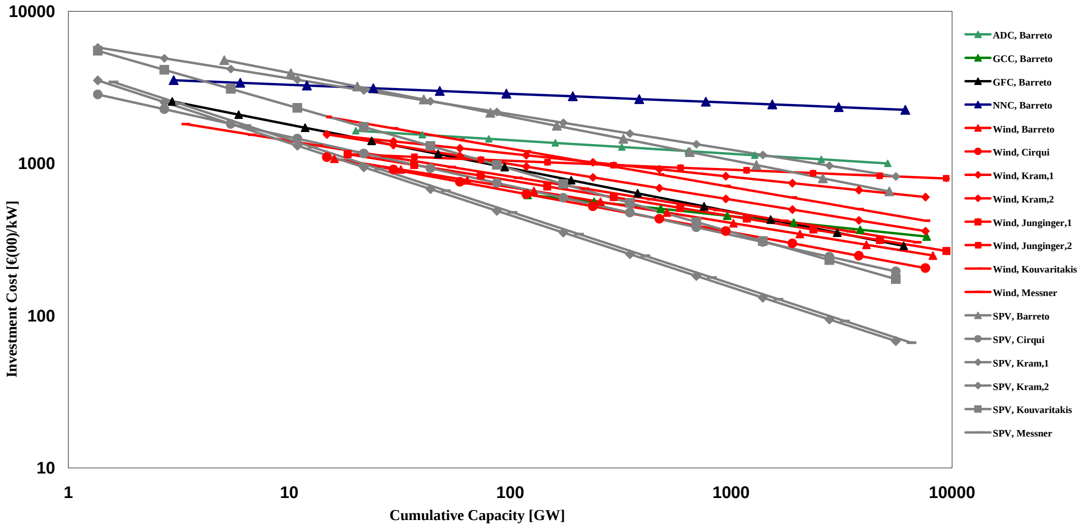

Figure 3-5: Investment cost development by uncertainty in PRs

3.2.1.1 Methodology developed to handle uncertainty of learning rates

Three different progress ratios are considered for each type of learning technology and each type of progress ratio is taken for all technologies at a time, to perform a scenario run. Therefore three different scenario runs has been performed in this study, i.e., one for maximum value, one for medium value and one for minimum value of progress ratios. The development of specific cost with respect to cumulative capacity is different for same technology for different values of progress ratio, which is presented in the Figure 3-6 and Figure 3-7 for CCGT technology for minimum (Min), medium (Med) and maximum (Max) value of the progress ratios. The percentage development of the specific cost and cumulative capacity with respect to their maximum values, of six segmentations of all learning technologies considered inside this study, is presented in the Figure 3-8.

Different progress ratios see very wide range variation of specific cost for the attainments of same value of cumulative capacity. Thus the model results will be influenced by a great extent for the uncertainty of the progress ratios. To freeze this problem, the floor cost approach has been developed and implemented inside the learning scenarios analysis. In learning theory, the floor cost is the cost of the last segment of the MIP approximation. In this study the floor cost for all progress ratios of all technologies calculated externally and inserted in the optimization subroutine, in which, same technology see the same specific cost at the initial phase and final stage (floor cost) irrespective of the progress ratios. This approach represents the reality of the technology specific cost development, i.e., the technology cannot learn thought out its development, rather it saturates at certain point of its cumulative capacity development, e.g., solar PV system consists of different components, in which some components learn and some components do not; and also the technology cannot learn as a whole to approximately zero investment cost because of the existence of non-learning components those has certain investment. The specific cost and cumulative capacity for the year 2005 are taken for the calibration of the learning parameters inside this study. The floor cost (lowest specific cost that the learning technology can attain) for different technologies are considered from the study of /Enq.-Kom./.

The development of the specific cost of the learning technology in MIP approach depends on the intial specific cost of the technology, initial cumulative capacity of the technology, maximum cumulative capacity the technology can attain, the progress sratio and number of segments of the technology in learning concept. In MIP approximation of the learning curve, it takes the value of cumulative capacity of the kink points and its corresponding total cumulative cost. Therefore the development of the MIP approximation and the standard parameter required for this is essential to study for the learning technologies.

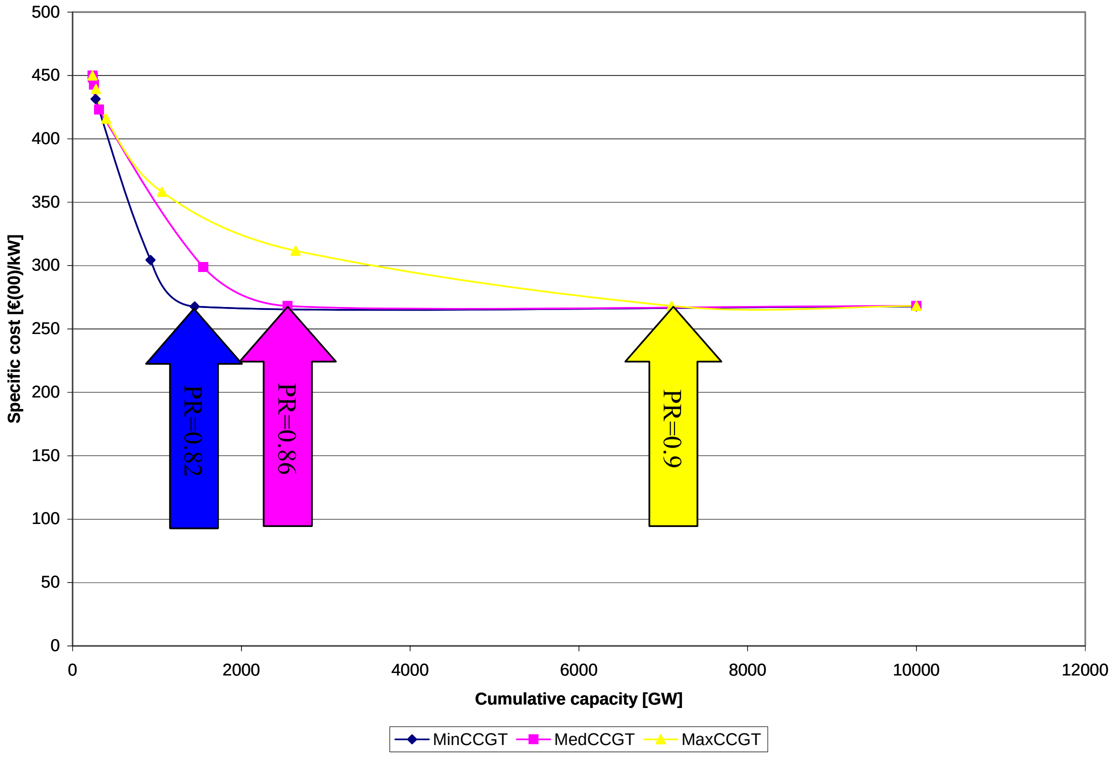

Figure 3-6: Specific cost development from learning curve

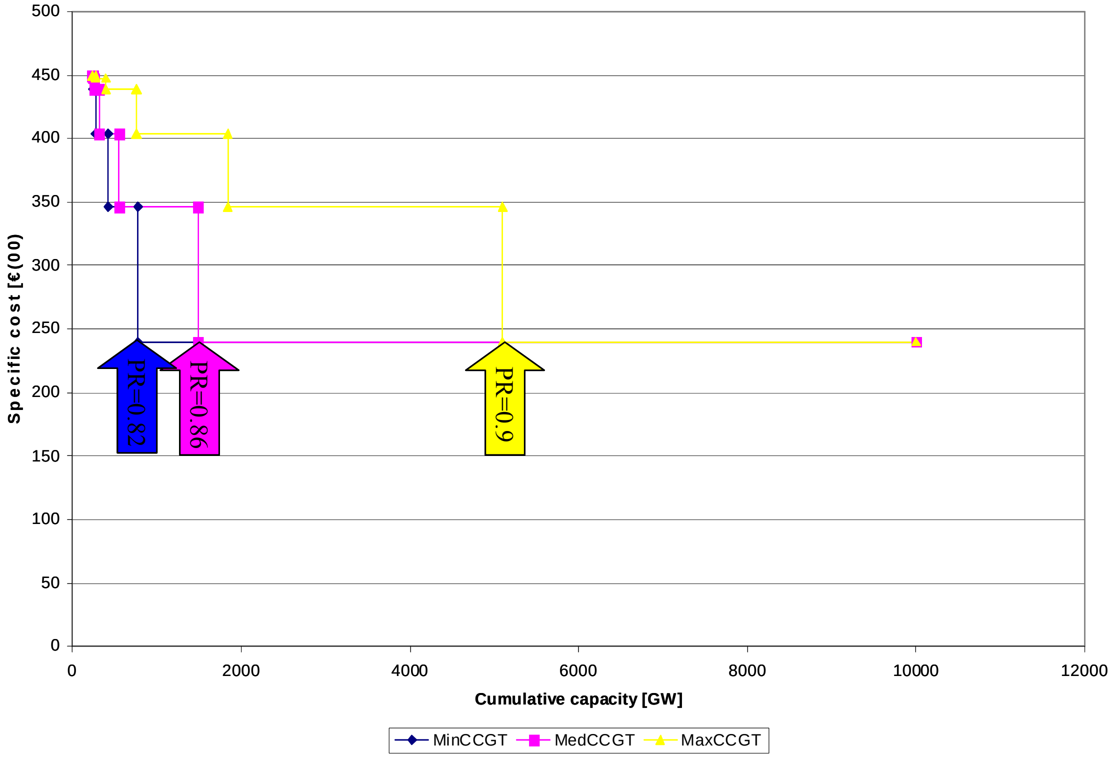

Figure 3-7: Specific cost development from MIP approximation of learning curve

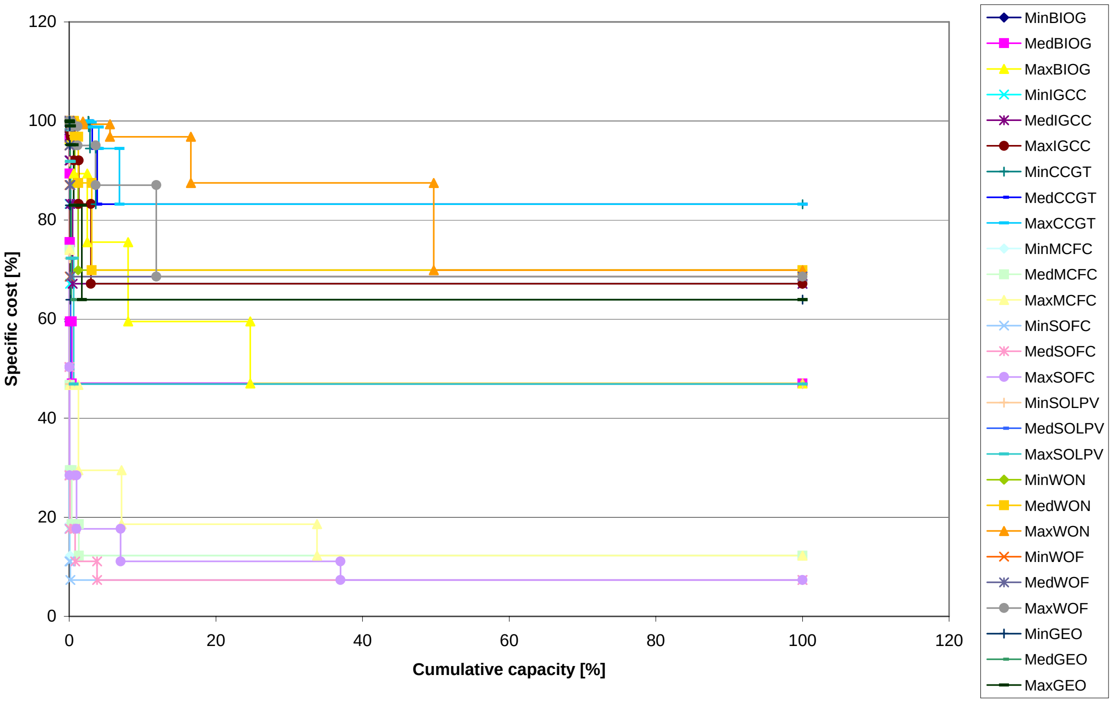

Figure 3-8: MIP segmentation on specific cost of all learning technologies

3.2.1.2 Assumptions taken for learning scenarios

The assumption on learning technologies those are considered inside the study and their parameters are provided in this sub-secton. Nine learning technologies are considered inside TIMES G5 model, those are biogasification (WEBION3), integrated gasification combined cycle (WECOLN3), combined cycle gas turbine (WEGASN3), molten carbonate fuel cell (WEMCFCN), solid oxide fuel cell (WESOFCN), solar PV (WESOLN2), wind onshore (WEWINN1), wind offshore (WEWINN2) and geothermal heat pump (WRGEOT). Assumptions on learning parameters like initial unit specific cost, floor cost, values of different progress ratios taken for the sensitivity analysis on uncertainty in learning rates (minimum, medium and maximum), number of segments, initial cumulative capacity and maximum cumulative capacity is provided in the Table 3-2. The kink points subject to uncertainty in learning rates (minimum, medium and maximum) and the corresponding parameters like cumulative capcity and total cumulative cost are provided in the Table 3-3. The starting period of the learning technologies for learning scenarios is given in the footnote[2].. Six number of segments are considered for the study for reliability from all corners as maximum number of segments has effect on the higher solution time and increase

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[2] Learning phenomenon is considered for WECOLN3 and WEGASN3 from 2010 onwards, for WEBION3, WEMCFCN and WESOFCN from period 2000 onwards; and for technologies WESOLN2, WEWINN1, WEWINN2 and WRGEOT from 1990 onwards.

in number of variables. On the other hand lower number of segements increase the average specific cost of the technology and affects the result.

Table 3-2: Assumption on learning technologies and their parameters

Assumption on learning technologies and their parameters								
Technologies	Ini. Spe. Cost.	Floor Cost	PR [Min.]	PR [Med.]	PR [Max.]	Number of Segments	Ini. Cum. Cap.	Max. Cum. Cap.
	[€(00)/ kW]	[€(00)/kW]	[dec. fra.]	[dec. fra.]	[dec. fra.]	[Integer]	[GW]	[GW]
WEBION3	2600	1200	0.89	0.92	0.95	6	0.0700	7000
WECOLN3	1350	900	0.89	0.92	0.95	6	2.0720	8000
WEGASN3	450	375	0.82	0.86	0.90	6	236.0000	9000
WEMCFCN	7500	900	0.82	0.86	0.90	6	0.0146	10000
WESOFCN	11000	700	0.82	0.86	0.90	6	0.0023	10000
WESOLN2	4500	2100	0.72	0.79	0.85	6	0.02	9000
WEWINN1	1170	800	0.81	0.89	0.96	6	0.6	9000
WEWINN2	1750	1200	0.86	0.91	0.96	6	0.015	9000
WRGEOT	670	430	0.82	0.86	0.92	6	5.0	25000

Table 3-3: Total cumulative cost and capacity at kink points

Minimum progress ratio									
Cumulative capacity [GW] at breaking points									
	WEBION3	WECOLN3	WEGASN3	WEMCFCN	WESOFCN	WESOLN2	WEWINN1	WEWINN2	WRGEOT
CCAPK0	0.07	2.07	236.00	0.01	0.00	0.02	0.60	0.02	5.00
CCAPK1	0.09	2.54	236.11	0.02	0.01	1.13	56.03	2.51	15.16
CCAPK2	0.11	2.60	236.68	0.08	0.10	1.14	56.37	2.54	15.31
CCAPK3	0.21	2.95	239.51	0.42	0.58	1.20	58.08	2.72	16.10
CCAPK4	0.70	4.66	253.67	2.10	2.98	1.51	66.65	3.62	20.01
CCAPK5	3.14	9.35	324.47	10.50	14.98	3.22	109.45	5.97	39.58
CCAPKM	7000.00	8000.00	9000.00	10000.00	10000.00	9000.00	9000.00	9000.00	25000.00
Total cumulative cost [M€(00)] at breaking points									
TC0	218782	3362515	148802890	153111	34987	4670386	29312603	1245085	7421328
TC1	271680	3977699	148853863	170968	65534	9670219	94152413	5607827	14225331
TC2	319563	4067126	149108620	535393	526881	9724607	94552575	5670686	14330055
TC3	541809	4508553	150379801	1686172	1831601	9992542	96542424	5982144	14849160
TC4	1481004	6604906	156672529	5316540	5881470	11245531	106237916	7478789	17344871
TC5	5182350	11778359	186762798	16767029	18615522	16773320	150050566	11056829	28222578
TCM	8364464290	7127588903	3434565505	9003199517	7004793378	18909678556	7417906336	10802859406	10719233350
Medium Progress Ratio									
Cumulative capacity [GW] at breaking points									
	WEBION3	WECOLN3	WEGASN3	WEMCFCN	WESOFCN	WESOLN2	WEWINN1	WEWINN2	WRGEOT
CCAPK0	0.07	2.07	236.00	0.01	0.00	0.02	0.60	0.02	5.00
CCAPK1	0.10	2.74	236.55	0.02	0.01	1.13	56.60	2.55	15.30
CCAPK2	0.37	3.13	238.75	1.56	1.44	1.19	59.18	2.83	15.94
CCAPK3	1.48	4.69	247.57	7.73	9.17	1.42	69.48	3.97	18.48

CCAPK4	5.88	10.94	282.82	32.42	80.11	2.33	110.67	8.50	28.66
CCAPK5	23.98	35.92	343.82	131.17	378.86	6.79	275.43	14.02	69.38
CCAPKM	7000.00	8000.00	9000.00	10000.00	10000.00	9000.00	9000.00	9000.00	25000.00
Total cumulative cost [M€(00)] at breaking points									
TC0	206887	3179700	135734710	139665	31914	2711812	13996612	721435	6179702
TC1	282591	4065277	135982499	163553	76563	7719302	79458283	5152496	13075554
TC2	905472	4570680	136972402	5410976	4973733	7973827	82453220	5643204	13498916
TC3	3021967	6525249	140912378	18925020	21173829	8953109	94224805	7545895	15157389
TC4	10194224	13739601	156380444	58086406	115378056	12429223	138788591	14574299	21363945
TC5	35127291	39109460	182199801	173385180	389115305	25150986	296325831	22465349	42661922
TCM	8368359361	7131335333	3419038982	9053323439	7120421969	18770277528	7420487809	10806942707	10716347089
Maximum Progress Ratio									
Cumulative capacity [GW] at breaking points									
	WEBION3	WECOLN3	WEGASN3	WEMCFCN	WESOFCN	WESOLN2	WEWINN1	WEWINN2	WRGEOT
CCAPK0	0.07	2.07	236.00	0.01	0.00	0.02	0.60	0.02	5.00
CCAPK1	0.12	3.18	239.14	0.02	0.01	1.13	57.77	2.62	15.58
CCAPK2	43.33	15.50	248.58	8.78	6.12	1.59	168.19	27.28	25.89
CCAPK3	172.96	52.46	276.87	125.08	99.45	2.97	499.45	101.26	56.81
CCAPK4	561.84	103.34	361.76	713.97	699.45	7.11	1493.23	323.21	149.57
CCAPK5	1728.48	235.98	616.43	3380.63	3699.45	21.01	4474.58	1069.04	427.85
CCAPKM	7000.00	8000.00	9000.00	10000.00	10000.00	9000.00	9000.00	9000.00	25000.00
Total cumulative cost [M€(00)] at breaking points									
TC0	196544	3020736	125236306	128862	29446	1647973	4860184	306260	4749194
TC1	331257	4489715	126649695	164423	106761	6652061	71682934	4861698	11826073
TC2	75610708	19469346	130873101	29361859	23897707	8633673	195972316	44072421	18485024
TC3	272416502	60212843	143401551	279201186	254147741	13918214	545824114	151424649	36904665
TC4	811033990	112809958	179904596	1222975512	1328780880	27137807	1529949579	451378585	86484724
TC5	2296018299	242338072	282696095	4571789181	5456018214	62234707	4297660162	1391416765	218013546
TCM	8594638616	7157834853	3416744572	11620926036	12753840173	18916426250	8295621546	10910828258	10740580009

3.2.2 Global learning

Technological learning on the basis of regions is difficult to handle in multi-regional energy system models, for the uncertainty and inconsistency associated with learning rates (1-progress ratios), initial cumulative capacity and learning parameter. Thus, it is useful to analyze the technological learning in global domain. In global learning, each region participates in the learning process and adds their capacity to the learning process for the development of future specific cost of the Learning Technologies (LT). Thus in global learning, all regions get the benefit by adding their capacity to the common learning process to reduce the specific cost of the technology than what the region expects when they learn individually. Indeed global learning benefits all regions from the cost point of view.

Global learning is considered as learning in one domain, i.e., single learning curve development for each type of technology for whole globe. One additional region has been created in this approach, which works as the manufacturing region or production centre of the learning technologies. In other word in can be presented as each region adds their capacity to the aggregate learning curve. The learning region takes the investment decision for each learning technology of real regions in the same time period.

Technological knowledge spills from leading regions to lack regions and the process of spillover needs time. This is presented in global learning concept as technology developed in one region and dispersed into different regions in different time periods. As the cumulative capacity is taken as proxy for knowledge development in learning theory /Barreto 2001/, therefore the knowledge spillover from one region to another can be depicted as the capacity transfer, that states the capacity developed in one region and takes some time to spill for integration into the energy system of another region /Gielen et al. 2004/. This reflects the procurement of investment made today for the development of the capacity to be utilized tomorrow. The time lag for capacity transfer to be utilised is no other than the technology gap or knowledge gap. This arises due to the knowledge lack by the developing regions to utilize the technology.

In this study technology gap or knowledge gap is approached in two different ways. One is the time lag for the technology to disperse inside the energy system of different regions and in another, the developing regions those are lacking knowledge, see higher specific cost of the technology if they are going to utilize the products developed in same time period.

The level of knowledge on global learning concept affects the model solution as both developed and developing regions use the same same technology, although they have the difference level of knowledge for the technologies, before their commcerialisation phase or during their early stage of commercialisation. After fully commercilisation of the technology, the knowledge spillover takes place through the product dissemination /Neij et al. 2000/ from developed regions to developing regions. By this process both developed and developing regions will achieve the same level of knowledge at a certain phase of the technology for which they have not to pay more investment cost for the utilization of the same technology in same period like developed regions. To develop the methodological approach for handling the knowledge spillover effect between developed and developing regions on the ground of additional investment cost is interesting. Only one manufacturing region is required for technology gap presented by time lag concept, where as technology gap in terms of additional specific cost requires two manufacturing regions. The additional region develops the additional investment cost for the knowledge lack regions in the form of knowledge lack technology.

3.2.2.1 Global learning without knowledge gap

Each region adds their capacity to the aggregate learning curve. In other way, it can be represented that each region integrates the technology having the same specific cost in the same period and also they use the same technology having the same technological specification. The learning region has taken the investment decision for each learning technology for real regions in same period. In this study all regions are divided into three region groups, consist of manufacturing region as (m), developed regions as region group (rg1) and developing regions as region group (rg2). This approach stands on the solid base of fictive commodity balance. The mathematical equation of fictive commodity balance, i.e., the commodity based capacity balance and the fundamental equation of the new capacity balance has been provided below, based on which global learning works.

$$FC_{IRE,T,IO} \pm \sum_{v} VAR\_NCAP_{R,V,T,P} = 0\,, \qquad \text{Equation 26}$$

$$TC_{m,te,t} = \int_0^{C_{te}} a \cdot C_{m,te,t}^{-b} * dC = \frac{a}{(1-b)} \cdot C_{m,te,t}^{(-b+1)}\,, \qquad \text{Equation 27}$$

and

$$C_{m,te,(t+1)} - C_{m,te,t} = \sum_{rg1=1}^{N} NCAP\_COM_{rg1,te,(t+1)} * p_{rg1,te,t+1}$$
$$+ \sum_{rg2=1}^{N} NCAP\_COM_{rg2,te,(t+1)} * q_{rg2,te,t+1}\,, \qquad \text{Equation 28}$$

where,

v є {t-Tech. Life,v}

$FC_{IRE,T,IO}$ is the fictive commodity related to the inter-regional exchange,

$VAR\_NCAP_{r,v,t,p}$ is new capacity variable,

Region group m represents the manufacturing region.

Region group rg1 contains {EU25, R_OECD},

Region group rg2 consist of {INDIA, CHINA, R_NOECD},

a is the unit specific cost of the technology,

b is the learning index of technology,

$C_{m,te,t}$ is the cumulative capacity of the technology te in manufacturing region m in time period t,

$P_{rg1,te,t}$ and $Q_{rg2,te,t}$ are the amount of capacity transfer to respective region groups, and

$NCAP\_COM_{(rg1,rg2),te,t}$ is fictitious commodity (commodity based on capacity) represents the unit investment level of the technology te in time period t.

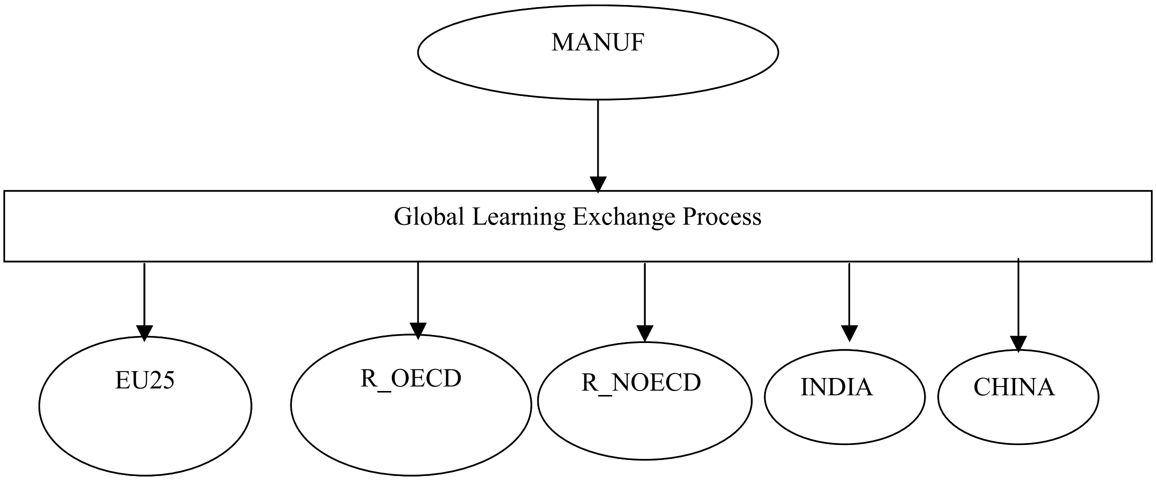

Figure 3-9: Global learning in multi-regional sphere

3.2.2.2 Global learning with knowledge gap

In this approach, knowledge gap is presented in terms of additional cost, i.e., the developed and developing regions see different specific cost in same time period if they are going to use the same technology produced in same time period in manufacturing region. The specific cost arises by knowledge lack, also learns itself with respect to accumulation of knowledge, i.e., reduces as the cumulative capacity increases. This intelligibly articulates that the developing regions and developed regions see same specific cost at very high value of cumulative capacity. The mathematical equations of this approach are provided below and graphical presentation is given in the Figure 3-10.

$$INVCOST_{dpd,te,t} = a * C_{m,te,t}^{-b} , \qquad \text{Equation 29}$$

$$INVCOST_{dpe,te,t} = a * C_{m,te,t}^{-b} + d * C_{m2,te,t}^{-b} , \qquad \text{Equation 30}$$

$$VAR\_NCAP_{m,te,t} = \sum_{rg1=1}^{5} VAR\_NCAP_{rg1,te,t} \qquad \text{Equation 31}$$

$$VAR\_NCAP_{m2,te,t} = \sum_{rg2=1}^{3} VAR\_NCAP_{rg2,te,t} \qquad \text{Equation 32}$$

where,
a is the unit specific cost of the technology,
d is the unit specific cost due to knowledge lack or technology gap,
b is learning index of the technology,
m is the manufacturing region,
m2 is the manufacturing region 2,
dpd is for developed regions,
dpe is for developing regions,

rg1 is the region group consist of both developed and developing regions,
rg2 is the region group consist of developing regions,
$C_{r,te,t}$ is cumulative capacity of technology te in time period t,
$INVCOST_{te,t}$ is investment cost of the technology (specific cost) te in time period t, and
$VAR\_NCAP_{m,te,t}$ is new capacity of the technology te in time period t on region 'm'.

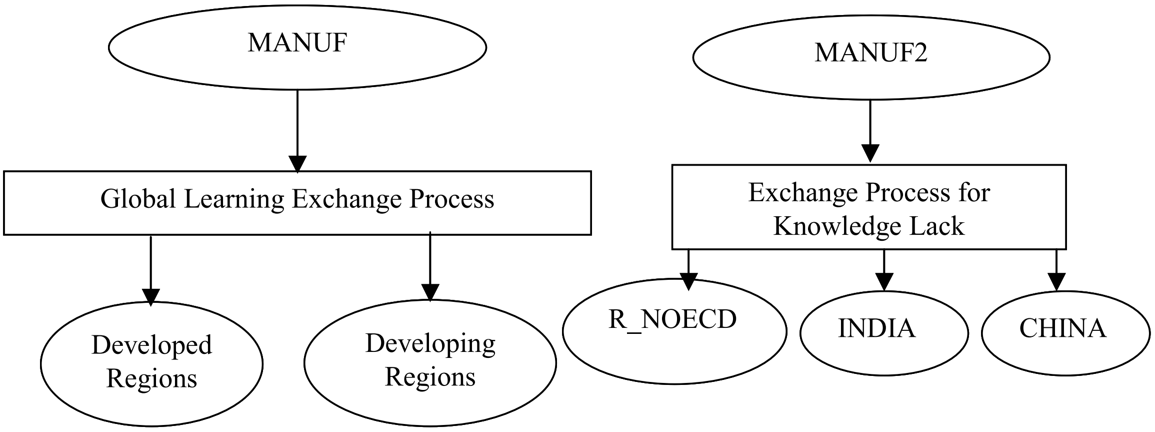

Figure 3-10: Global learning in knowledge gap concept

Figure 3-11 depicts how the developing regions and developed regions see different specific cost, if they utilize the same product in same time period in global learning concept. The difference of specific cost (204 €(00)/kW) of wind technology, which arises due to knowledge gap between India (1525 €(00)/kW) /Narain et al. 1997/ and Germany (1321 €(00)/kW) /Kruck et al. 2004/ in period 1990 is taken as knowledge gap or technology gap between developing and developed regions. This diffence of specific cost is taken as the knowledge lack for developing regions and mapped as a technology to represent the knowledge lack in developing regions. This knowledge lack technology learns itself and attains nearly zero specific cost at very high value of the cumulative capacity. The knowledge lack in developing regions in the form of additional investment cost has been modeled inside the database of developing regions is picturised in Figure 3-12. The production of electricity or same commodity requires to pass through two learning curves for developing regions and the input to the knowledge lack technology is the environmental heat that cost zero. The specific cost development for other learning technologies are mapped like wind technology between India and Germany.

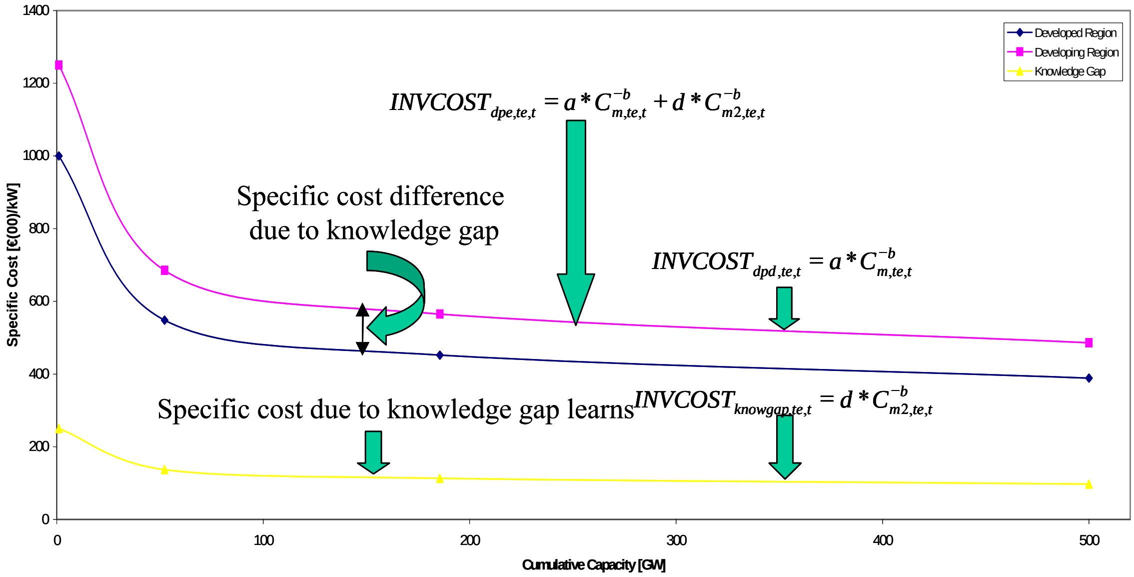

Figure 3-11: Different specific cost by knowledge gap

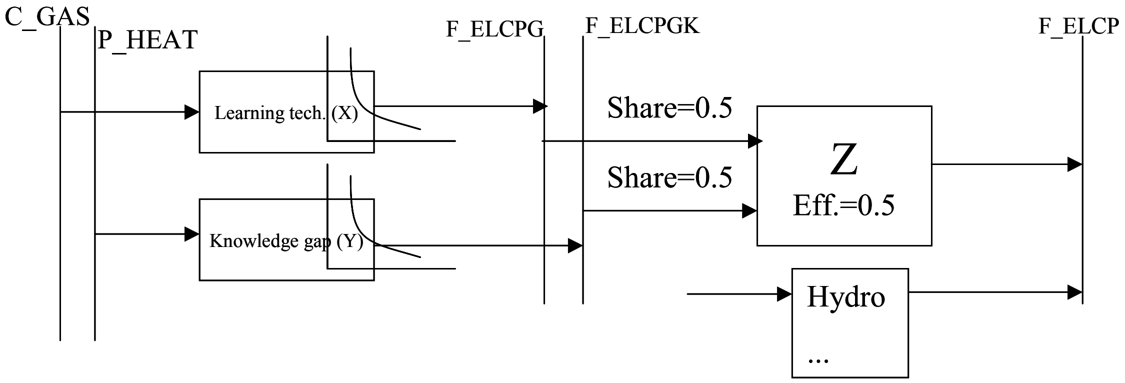

Figure 3-12: Knowledge gap modelled inside the database

3.2.2.3 Global learning with technology gap presented by time lag concept

The concept of time lag is rather said to be technology gap, which reflects that the technology will be developed today and will be consumed in future. The investment cost associated with the technology is already known today but it will integrate into the energy system of somewhere in future. This is quite interesting to know how the energy optimization model handles the technology gap and how it influences the model result. In regional single factor learning curve, the amount of the new capacity developed in certain time period is equal to the amount of the new capacity consumed in that period, as there is one new capacity variable in one regional index. In this study, five regions have been divided into two regional groups. One is developed region (EU25 and R_OECD) and the other one is developing region (R_NOECD, INDIA and CHINA).

Investment decision for the time period ‘t’ of developed regions and investment decision for time period (t+lag) of developing regions has been taken by the manufacturing region in time period ‘t’. In other words it says that the new capacity required in time period ‘t’ of developed regions and the new capacity required in time period (t+lag) of the developing regions add to the learning process in time period ‘t’. It directly says that the developed regions utilise the technology, developed in manufacturing region on the same time period, whereas the developing regions use the technology manufactured in the period (t+lag).

Also, it can be tested in this approach that the technology gap may or may not persist for whole period of the model and may reduce to zero in future at certain point. For example the technological gap will persist till 2040 and after that the technology gap will be zero. So at this point the specific cost visualized by both the regions are equal after the freezing point of technology gap, i.e., period 2040 or any as assumed. In this condition, it generates curiosity how the regional energy system interacts with the learning technologies. The concept behind the discontinuities in the time gap is coming from the improvement in information exchange (may be instantaneous), economic development, market development mechanism, etc.

The time lag concept is handled at the level of fictive commodity balance. It says that, out of the total new capacity produced in time period ‘t’ in learning region is the summation of the consumption of the total new capacity in developed region in time period ‘t’ and in the developing region (t+1). The investment decision for developing regions for time period (t+lag) and for the developed regions in time period ‘t’ has been taken by the learning region in time perod ‘t’. Therefore the technology used in developed regions in time period ‘t’ will have same specific cost of developing region used in time period ‘(t+lag)’. Taking the discount factor into consideration the fictive specific cost seen by developing regions will be $(1+d)^{\text{lag in years}}$, where ‘d’ is the discount factor.

$$\begin{aligned} C_{m,te,(t+1)} - C_{m,te,t} &= \sum_{rg1=1}^{N} NCAP\_COM_{rg1,te,(t+1)} * P_{rg1,te,t+1} \\ &+ \sum_{rg2=1}^{N} NCAP\_COM_{rg2,te,(t+1+lag)} * Q_{rg2,te,(t+1+lag)} \end{aligned} , \qquad \text{Equation 33}$$

$$\begin{aligned}&C_{m,te,(t+1)} - C_{m,te,t} = \sum_{rg1=1}^{N} NCAP\_COM_{rg1,te,(t+1)} * P_{rg1,te,t+1}\\&+\left[\sum_{rg2=1}^{N} NCAP\_COM_{rg2,te,(t+1+lag)} * Q_{rg2,te,(t+1+lag)}\right]_{t\leq T} + \quad ,\\&\left[\sum_{rg2=1}^{N} NCAP\_COM_{rg2,te,(t+1+lag)} * Q_{rg2,te,(t+1+lag)}\right]_{t\rangle T}\end{aligned}$$

Equation 34

where,
m represents the manufacturing region,
$C_{m,te,t}$ is the cumulative capacity of the technology te in manufacturing region m in time period t,
$P_{rg(1,2),te,t}$ is the amount of capacity transfer to respective region groups, and
$NCAP\_COM_{(rg1,rg2),te,t}$ is fictitious commodity that represents the unit investment level of the technology te in time period t, and
lag is the technological gap or time lag on technology spillover.

Equation 33 portrays about the new capacity development in the manufacturing region, when there persists continuous technology gap in-between developed and developing regions for the whole model horizon. Likewise discontinuous in technology gap is presented in the Equation (34), which demonstrates that there exists knowledge lack in-beteen developed and developing regions till certain time farme and after that it vanishes, which represents the knowledge lack drops from state one to state zero.

The technology gap on global learning is valid, for those technologies, which satisfies the condition of (lag+1) period will be less than equal to the technical lifetime of the technology in the form of period duration. The new capacity installation of the learning technology in the technology lag regions will take place after lag period of the technology development in manufacturing region. Technological gap represents the reality of the technology flow from the developer to consumer. Low technology gap, short period duration and high technical lifetime favour the model results and simontaneously the reverse phenomenon is true.

4 Overview of TIMES G5 Model

Energy system modelling, which coevolved from socio-technological interaction in terms of technological dissemination, and their interaction with the economy plays a key role in the elaboration of national and international strategies to combat the threat of climate change /Acropolis 2001/, dissolve the problem of energy poverty, change in the structure of future energy supply, reflect path towards technological sustainability, formulation and implementation of national and international policies.

Modeling of energy system holds certain purpose and bears fundamental concept of energy demand fulfillment economically, which gained more importance as economically energy supplying, came to the forefront of the debate in each and every time. Not only the modeling aspect should focus only on the lowest cost of energy production but also it should stress on climate change, local and global environmental impact. Furthermore, energy system modeling predicts the behaviour of future energy system and interplay of technology, taking account of present situation, attitude of human being towards the technologies, fuel availability, government policies, pollution and other related factors. Energy systems models are employed as a supporting tool to develop energy strategies, outlining the likely future structure under particular condition and, thus, provides insights into the technological paths, structural evolution and policies that should be followed in future /Mattsson and Wene 1997/.

The study used the TIMES model generator for the development of five regional gobal energy system model as the TIMES is a better model generator and overcome many disadvantage of MARKAL and EFOM on modeling aspect. Firstly, it is based on linear programming approach; it has flexibility in modeling of the process, time resolution and quite flexible in change of time horizon of the model. TIMES model generator is suitable to handle the learning curve phenomenon of the learning technologies in MIP approach. It handles the MIP approach well inside the optimization subroutine.

4.1 TIMES model generator

TIMES (**T**he **I**ntegrated **M**arkal **E**fom **S**ystem) is a process-analytic, dynamic optimization model of the entire energy system based upon which the TIMES G5 model stands. TIMES was developed within a working group of the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency (IEA) /Remme et al. 2001/, /ETSAP 2002/. The TIMES development pursues advantages over existing energy system models like MARKAL /Goldstein, Greening 2001/ and EFOM /Voort et al. 1984/ by eliminating some modeling shortcomings in these models and creating a modeling environment being readily adaptable to new ideas and methodologies. In reality, TIMES is a model generator and follows bottom-up system engineering approach with detailed techno-economic description of the energy system with interconnections of the processes (e.g., types of power plants or technologies) and commodities (energy carrier, cost, material, emission, etc.) in the form of a so-called Reference Energy System (RES). In the RES the commodities flows through the process and the process represents itself a technology as depicted in Figure 4-1. This approach facilitates diagrammatical analysis of the whole energy system starting from production to sector-wise useful energy consumption through different conversion processes.

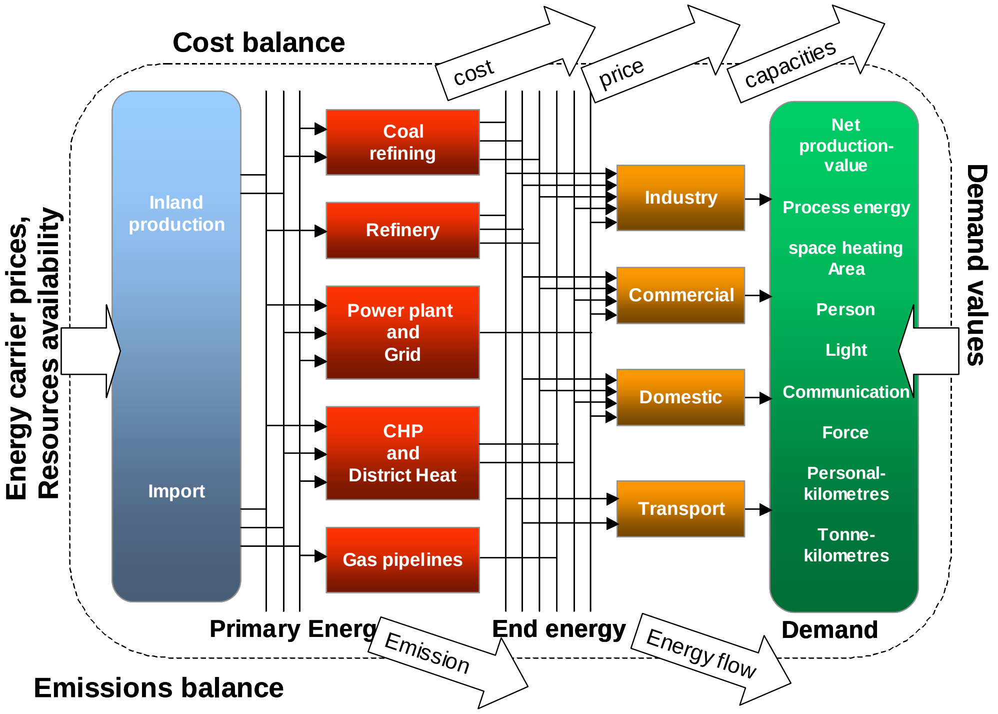

Figure 4-1: Schematic illustration of a reference energy system

The energy system is interpreted mathematically by mathematical equations of equalities and inequalities subject to optimization of an objective function representing cost (minimization) or profit (maximization) by fulfilling certain energy demand. Apart from this there are different goals behind the development of different global, regional, local and sectoral energy models, which solely depends on the developer and their associated objectives. TIMES is based on least cost optimisation model, which reflects the optimisation of the entire energy system cost in a given time frame. TIMES model generator is suitable for time resolution and shifting of the time horizon. At present TIMES has integrated many advanced features of MACRO economic linkage (top-down model of NLP approach), MIP approach of endogenous learning, MIP approach of discrete capacity extension, parametric uncertainty by stochastic programming, advanced modeling of CHP plants, e.g., passout turbine or extraction-condensing turbine and climate module integration.

4.2 Reference Energy System (RES) of TIMES G5 model

Whole globe has been divided into five regions in this study. The formulation of the regions are European 25 nations (EU25), Rest of OECD countries (R_OECD), Rest of Non-OECD countries (R_NOECD), India and China and the model is developed in TIMES and named as TIMES G5 model. The starting peiod of the model is 1990 with 5, 8 and 10 years of period duration and the model covers more than 100 years of the energy study of each region, i.e., the study covers the model horizon from 1990 to 2100. The global TIMES G5 model has been stood on some basic parameters and their assumptions; those are the drivers of energy demand. The basic drivers of the TIMES G5 model are the population and GDP (see chapter 4.3). The overall Reference Energy System (RES) of any energy system can be depicted diagramically as shown in Figure 4-2, where the commodities and processes are interlinked. It is easy and compatible to visualize the technologies and the commodities those are inside the model and also quite comfortable to check and change according to the requirement. The RES of all five regions of the TIMES G5 model are same and its overall view is shown in Figure 4-2. The model developed inside this study has many advanced features, which can pave the road map to future energy system in different angels.

Various modeling aspects have been covered inside this study starting from extraction to end use sectors. The modeling of the reserve and resource by each region reflects their availability to be economically extracted and the ability of that specific region to extract the energy carriers to fulfill its future energy demand (see chapter 4.5). Four energy carriers of hard coal, lignite, crude oil and natural gas been modeled in four conceptual steps, i.e., in each step, the amount of resource and reserve can be extracted by certain cost. If the region is lacking the availability of the resource and reserve then it can import the energy carriers from the other regions through inter-regional exchange processes. In this respect the region specific models are connected to each other through the inter-regional exchange of the commodities like hard coal, crude oil, natural gas, Liquefied Natural Gas (LNG), electricity, diesel, petrol, Liquefied Petroleum Gas (LPG), kerosene and hydrogen. LNG and hydrogen are specially modeled, because those are of special interest as future energy carriers. During the modeling of the hydrogen, it was kept in mind that may be in future the transportation of the hydrogen from one region to another will take place as the production of hydrogen from one region to another may vary to a great degree according to the availability of the resource and production technology. From the point of technological learning theory, may be one region will have enough resource to utilize the natural fuel carriers to produce the hydrogen to transport to other regions. For example the Sahara desert of Africa, Thar Desert of India, Gobi and Aklimakan desert in China can use solar technologies to produce hydrogen in future, hydrogen from hydropower in Canada, when the technology may be cheap by attainment of the break-even point. Like-wise the wind concept cannot be omitted. The liquefaction and gasification units are modeled for the production of LNG that will be exported from one region to another.

The refinery sector is modeled to supply the petroleum products upon which the transport sector relies heavily. Refineries are modelled inside each region with their past investments. They produce the secondary energy carriers out of primary crude oil to fulfil the petroleum demand in the host region and also to other regions, as the inter regional exchange for diesel, petrol, kerosene and liquefied petroleum gas has been modeled in inter-regional exchange. The decision for the future refinery capacity installation has been opened to each region according to the economic point of view, i.e., they may build the refinery capacity to produce the petroleum products for them or they may import the refinery products depending, which is cheaper for them. The modeling of end use sectors is furnished in this section (see chapter 4.4).

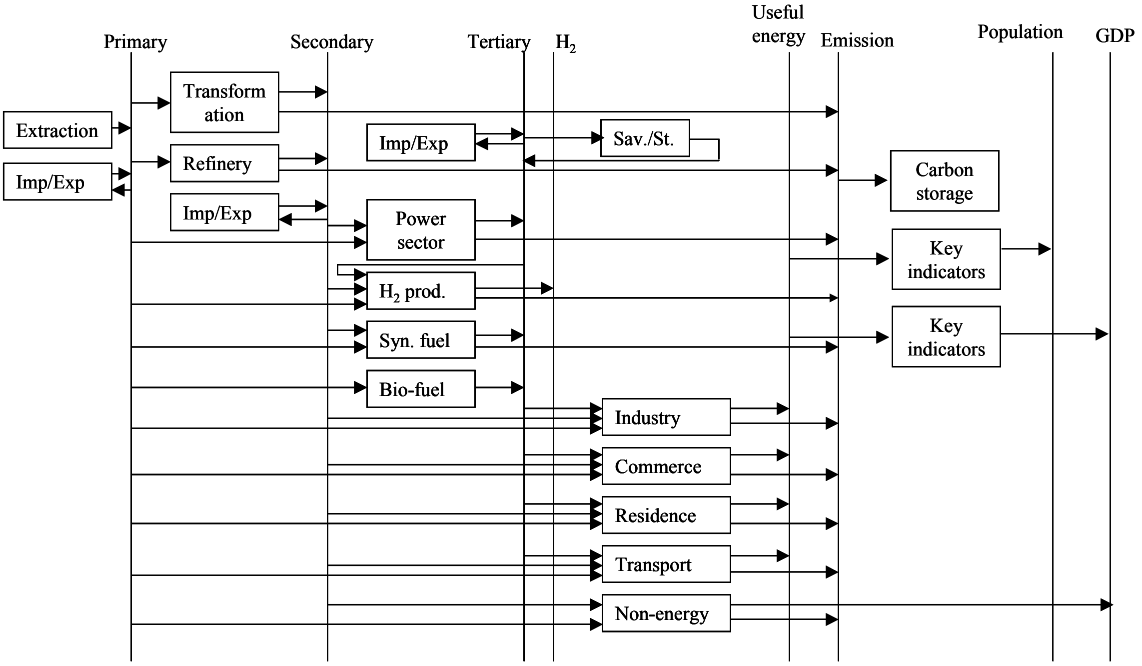

Figure 4-2: RES used in TIMES G5 model development

The forthcoming sections provide information on development of the key indicators, technological characterization and the modeling of reserves and resources.

4.3 Key indicators

The indicator approach in energy system analysis incites to understand, how economic and technical factors shape the energy use, its positive and negative outcomes. The energy indicator quantifies the amount of energy consumption per capita and energy consumed per unit production of GDP. Also it provides the information about the drivers of the energy use /IEA-India 2002/.

Energy indicators describe well, how energy is linked to socio-economic activities as well as indicates important relationship, trends and challenges /Schipper et al. 2000/. The variation of the indicators defined on regional basis depends on the structure of energy consumption, the energy consumption by type of industries and the composition of the fuel mix. The calculation of different indicators depends upon the modeller and their way of its representation. Therefore the indicators defined by variety of authors on certain data set may lack consistency as the source of their data collection and methods adopted for its calculation are different. The indicators can be defined on any two parameters, but they should have the logic behind the development.

4.3.1 Socio economic development

The population in the year 1990 of regions EU25, R_OECD, R_NOECD, India and China are respectively 431, 612, 2194, 850 and 1142 million /WEO 2004/, /Chinastat 1995/ and /India.census/. The region R_NOECD shows highest growth rate of population through out the model horizon and touch the figure of 5880 million in year 2100, whereas, India takes the second position by attaining the value 1729 million (see Table 4-1). The population growth rate of EU25 region increases till 2030 by attaining its highest value with 444 million and then onwards follow decline in trend through 2100 (336 million). The region R_OECD reaches its maximum value with 889 million in the year 2050 from 612 million in 1990 and declines to 844 million in 2100. Population of China more or less remains constant from 2030 to 2100. It slightly declines its growth rate from 2030 to 2050 and marginally inclines from 2050 to 2100. Total population of world reaches 8.2 billion in 2030, 9.145 billion in 2050 and 10.16 billion in 2100. The comparison of the assumptions taken inside this study could be realised with existing studies (see chapter 2.4.8).

All regions show positive growth rates of GDP from beginning to the end period of the model horizon. The growth rate of GDP is highest in China followed by India, R_NOECD, EU25 and R_OECD. The total GDP of world reaches around 103.6, 160.7 and 288.3 trillion €(00) respectively for the periods 2030, 2050 and 2100. Low GDP growth is realized by developed region and high for developing regions.

Table 4-1: Assumptions on GDP, population and related indicators

Average population growth rate [%/a]					
Region	1990-2000	2000-2030	2030-2050	2050-2100	
EU25	0.27	0.01	-0.47	-0.37	
R_OECD	1.06	0.72	0.26	-0.10	
R_NOECD	1.76	1.43	0.78	0.46	
INDIA	1.80	1.11	0.65	0.14	
CHINA	1.07	0.43	-0.05	0.04	
World	1.42	1.02	0.50	0.26	
Average GDP (ppp) growth rate [%/a]					
Region	1990-2000	2000-2030	2030-2050	2050-2100	
EU25	2.12	2.06	0.98	0.36	
R_OECD	2.92	2.21	1.31	0.56	
R_NOECD	1.62	3.47	2.95	1.70	
INDIA	5.44	4.29	3.28	1.41	
CHINA	9.84	5.24	2.73	1.21	
World	3.09	3.11	2.22	1.18	
Population [Million]					
Region	1990	2000	2030	2050	2100
EU25	431	442	444	404	336
R_OECD	612	680	844	889	844
R_NOECD	2194	2612	4005	4678	5880
INDIA	850	1016	1416	1612	1729
CHINA	1141	1269	1445	1430	1460
World	5228	6019	8154	9014	10250
GDP (ppp) [Billion €(00)]					
Region	1990	2000	2030	2050	2100
EU25	7249	8939	16472	20001	23924
R_OECD	11732	15649	30106	39071	51539
R_NOECD	8279	9725	27037	48380	112433
INDIA	1510	2564	9052	17264	34762
CHINA	1774	4535	20986	35969	65643
World	30545	41411	103653	160686	288300
GDP/capita [k €(00)/capita]					
Regions	1990	2000	2030	2050	2100
EU25	16.83	20.20	37.07	49.46	71.14
R_OECD	19.16	23.01	35.68	43.94	61.04
R_NOECD	3.77	3.72	6.75	10.34	19.12
INDIA	1.78	2.52	6.39	10.71	20.10
CHINA	1.55	3.57	14.52	25.15	44.97
World	5.84	6.88	12.71	17.83	28.13

The growth rate of GDP of /IEO 2004/ from 2001 to 2025 is assumed as 2.4%/a by industrialised countries, 4.6%/a for developing regions, 5.2 %/a for India and 6.1%/a for China, those can be compared with the adopted values given in the Table 2-6 /WEO 2004/. According to /Ito et al. 2000/, the total world GDP will grow at the rate of 2.58%/a from 1990 to 2050 and 1.8%/a from 2050 to 2100. In total GDP, the share of developed countries will decline from 69% in 1990 to 25% in 2100 /Ito et al. 2000/. The work of /Morita et al./ supposes that the world GDP will be in the range of 250 to 550 trillion US$. Other study by /Rajesh et al. 2002/ assumes the GDP growth by 5.5% per annum on an average during 2000–2025, by about 5% during 2025–2050, by 4.5% during 2050–2075, 3.5% during 2075–2085 and stabilizing at 2% by year 2100 for India. The economic condition of developed regions is coming under saturation and the developing regions are blooming.

4.3.2 Key indicators developed for different sectors

To visualize the future world energy demand, it is required to look inside the trends in energy consumption at the end-use sectors (industry, commerce (service+agriculture), residence, transport and non-energy use) at present and their behaviours in future /eia.oiaf.enduse/. Also each sectoral energy demands, those are further divided into different types of useful energy demand. Broadly the useful energy demand is taken for the purpose of heating, cooling, cooking and other electricity. Heating useful energy demand consists of hot water and space heating. Cooling useful energy consist of space cooling energy demand. Cooking useful energy provides the cooking energy demand for the household sector. Other electric energy demand consists of different appliances electricity demand.

4.3.2.1 Industry sector

In industry sector, two key indicators have been developed, one is the heat demand per GDP and the other one is the ‘other-electric’ demand per GDP. The development of the indicators is derived from the IEA statistics and WEO projections /WEO 2004/ of total final energy consumption in industry sector from the year 1990 to 2030. Other electric indicator has certain share in total electricity demand by industry sector, which goes towards the fulfilment of energy demand by electrical appliances and lighting devices of the industry. Rest of the electricity, out of total and other energy carriers are converted to their useful heat energy, by taking account of the technologies available to the respective energy carriers and energy efficiency improvement figures. The values of the indicators decrease from starting period to end period, representing that the growth rate of GDP is in higher side than the growth rate of industrial useful energy demand /eia.oiaf.enduse/. The development of the indicators and the values of those by regions are specified in the Table 4-2.

Table 4-2: Key indicators developed for industry sector

Key indicators developed for industry sector						
Indicators	Regions	1990	2000	2030	2050	2100
Heat/GDP [PJ/B€(00)]	EU25	1.130	1.009	0.860	0.732	0.665
	R_OECD	1.321	1.157	1.105	1.070	1.029
	R_NOECD	1.847	1.917	1.475	1.152	0.711
	INDIA	1.190	0.951	0.820	0.487	0.294
	CHINA	2.175	1.780	0.753	0.544	0.348
Other Electric/GDP [PJ/B€(00)]	EU25	0.378	0.370	0.277	0.263	0.251
	R_OECD	0.415	0.461	0.291	0.263	0.235
	R_NOECD	0.492	0.469	0.414	0.347	0.193
	INDIA	0.250	0.191	0.169	0.155	0.149
	CHINA	0.624	0.521	0.334	0.220	0.176

The value of the key indicators (PJ/€(00)) developed, differs from one region to another by the influence of several factors. The indicators are not developed on the basis of sector specific GDP, which makes a question mark on the share of industrial GDP on overall GDP by regions and with respect to time. Also, it brings to other points like the share of high, medium and low energy intensity industry in total industrial energy consumption. The higher share of high-energy intensity industry (cement, lime, glass, textiles, pulp and paper, non-ferrous metal, iron and steel, aluminium, etc.), the higher is the key indicator value and the reverse is true for low energy intensity industry. Basically the structure of industry sector, efficiency of the industry and its share in total GDP by regions affects the key indicators development /eia.oiaf.world/.

The higher values of industrial useful energy intensities for R_NOECD regions represent that the growth of energy demand is more compared to growth of GDP, which can be understood from the last decade economic collapse in Former Soviet Union (FSU) /eia.oiaf.world/. It is comparatively difficult to get the literatures, for comparison of the industry indicators developed in this study.

4.3.2.2 Commerce sector

The economic and population growth drives commerce sector activities by resulting higher energy demand. The increase in populations needs higher services (health, education, financial, government, etc.) and also higher levels of economic activity leads to disposable income, which increases demand for leisure requirements those increase energy demand. The specific electricity demand increases in commerce sector of all the regions as rapid growth of commercial activities, shifting of commercial activities and penetration of new and advanced electronic appliances will take place /eia.oiaf.world/ (see chapter 5.2.1.1 of Figure 5-6).

Three key indicators have been developed for commerce sector to fulfil the useful energy demand of cooling, heating and other electric. All useful energy indicators by regions are shown in Table 4-3. The key indicators are defined on commercial final energy demand taken from IEA /WEO 1994-2004/ for the years in-between 1990-2030. Different shares of each final energy carriers have been allocated towards the various useful energy demands. All the indicators are defined on overall GDP rather sector specific GDP.

Heating and cooling indicators decrease with progress of time, whereas the reverse phenomenon is observed in other electric demand indicator. One can easily find out the disparities among regions on the same indicator development. It is obvious and logical, that the heating indicator value is higher for cold climate regions and cooling indicator values for hot climate regions. The other electric demand indicator is higher for developed regions compared to developing region in the initial periods of the model horizon, which incites the degree of electrical appliances merged inside the commerce sector. The heating and cooling indicators for R_NOECD region is in higher side compared to all regions, indicating the fact of lagging GDP growth rate to energy demand and may be the commerce sector contributes more in total GDP.

Table 4-3: Key indicators developed for commerce sector

Key indicators developed for commerce sector						
Indicators	**Regions**	**1990**	**2000**	**2030**	**2050**	**2100**
Cooling/GDP [PJ/B€(00)]	EU25	0.034	0.040	0.047	0.062	0.083
	R_OECD	0.055	0.058	0.062	0.071	0.093
	R_NOECD	0.359	0.270	0.180	0.139	0.098
	INDIA	0.079	0.067	0.041	0.040	0.039
	CHINA	0.028	0.028	0.027	0.026	0.023
Heating/GDP [PJ/B€(00)]	EU25	0.443	0.422	0.324	0.315	0.299
	R_OECD	0.466	0.384	0.349	0.344	0.325
	R_NOECD	0.808	0.726	0.619	0.475	0.265
	INDIA	0.077	0.045	0.017	0.017	0.017
	CHINA	0.549	0.307	0.220	0.209	0.182
Other Electric/GDP [PJ/B€(00)]	EU25	0.182	0.186	0.159	0.154	0.148
	R_OECD	0.279	0.269	0.213	0.200	0.188
	R_NOECD	0.091	0.149	0.229	0.232	0.165
	INDIA	0.048	0.072	0.177	0.146	0.101
	CHINA	0.066	0.078	0.144	0.138	0.125

4.3.2.3 Residence sector

The economic development, growth of population, increase in living of standard, purchasing power of individual, rate of urbanization and size of accommodation per occupant has strong influence on the energy demand and penetration of modern appliances /eia.oiaf.world/ in a region. So the household energy demand is a good indicator for the development of human activities and their standard of life though it has a significant contribution to the total GDP in all regions. Generally household energy consumption share in total final energy consumption vary to a higher degree from country to country, depending on the consumption of the conventional and unconventional fuels, demand of various useful energy, types of technology used to serve useful energy demand, composition of income level of inhabitants, climatic condition, natural resource, security of fuel supply and available energy infrastructure /worldenergy.rural/.

The final energy consumption by residential sector varies from 45 to 60 % of the total final energy consumption by India and China, whereas variation from 18 to 26 % is found for R_NOECD, EU25 and R_OECD regions /WEO 2004/. Despite higher share of household energy consumption by developing countries in their total energy consumption, average per capita household energy consumption is too small, about nine times lower with respect to developed countries. Annual average household energy consumption was highest in United States with about 38 GJ/capita in 1990, followed by 28 GJ/capita in Netherlands, 19 GJ/capita in Republic of Korea, 18 GJ/capita in Japan, 5 GJ/capita in Asia, 3.3 GJ/capita in China and 0.36 GJ/capita in India /Dzioubinski et al. 1999/.

Space heating holds the largest share in end-use energy in the EU15 countries and accounts for 68.8% of total domestic consumption; water heating accounts 13.8%; lighting and electrical appliances accounts 12.8%; and cooking 4.6% /ademe.anglais/ in-between 1990 to 2000. In a survey of six low-income villages of South India reveals little variation in end-use shares of 76 to 81% for cooking, 14 to 19% for water heating and 2 to 3% for lighting by electricity and kerosene /Reddy 1982/. The survey of eight rural villages in Chile’s, much cooler climate area, reflects the cooking demand of 42 to 55% and space heating of 23 to 52%, while water heating 14 to 22%, except one village with 6% /Diaz and del Valle 1984/.

From the above figures, it can be concluded that the disparities in the development of each household energy demand indicator on useful energy depends on several factors. For the case of cooking, it depends on the type of fuels used, heating value of the fuel and the technology available to that fuel, efficiency of the technology, way of cooking devices utilised (open fire, three stone, etc.), employment rate, household size, number of meals cooked per day, income level of the family to spend on outside meal, cooking utensils used, varieties and types of foods cooked (e.g., cooking of kidney beans may require four or more hours to be boiled, whereas rice takes 20 to 30 minutes to be steamed). As well the mentality, traditional and cultural values cannot be omitted from the reasons of higher cooking energy demand. Some field measurements found that rice on an average takes 12 to 38 MJ per kg to cook and kidney beans 225 MJ/kg /worldenergy.rural/. Thus the number of verities of food items and types of food has great influence on cooking energy consumption per capita. Also cooking energy requirement for large household size and individual deviates greatly.

Table 4-4: Key indicators developed for residence sector

Key indicators developed for residence sector							**Energy consm. per capita**	
							kWh/day	kWh/day
Indicators	Regions	1990	2000	2030	2050	2100	1990	2100
Cooking/capita [PJ/M People]	EU25	0.670	0.688	0.973	1.013	1.064	0.510	0.810
	R_OECD	0.943	1.109	1.818	1.936	2.100	0.717	1.598
	R_NOECD	1.725	1.795	2.032	2.425	2.906	1.313	2.211
	INDIA	0.951	1.147	1.582	2.594	2.933	0.724	2.232
	CHINA	0.904	1.238	2.273	2.728	2.782	0.688	2.117
Cooling/capita [PJ/M People]	EU25	0.104	0.121	0.293	0.371	0.593	0.48	2.74
	R_OECD	0.199	0.236	0.408	0.436	0.489	0.92	2.26
	R_NOECD	0.147	0.253	0.775	1.400	1.796	0.54	6.65
	INDIA	0.024	0.360	1.107	1.992	2.656	0.09	9.84
	CHINA	0.019	0.359	1.117	1.821	1.857	0.07	6.88
Heating/capita [PJ/M People]	EU25	16.783	17.746	23.861	23.902	24.141	31.08	44.71
	R_OECD	14.756	16.892	18.461	18.484	18.516	27.33	34.29
	R_NOECD	1.533	2.062	2.973	4.028	4.838	5.68	17.92
	INDIA	0.828	0.892	2.152	2.290	2.371	3.07	8.78
	CHINA	1.354	1.765	3.437	5.670	5.727	5.01	21.21
Other electric/capita [PJ/M People]	EU25	2.449	3.197	5.209	6.358	6.867	1.864	5.226
	R_OECD	3.963	5.238	9.069	9.098	9.160	3.016	6.971
	R_NOECD	0.776	1.049	1.774	2.308	2.904	0.590	2.210
	INDIA	0.073	0.288	0.785	1.400	1.585	0.055	1.206
	CHINA	0.121	0.517	1.189	1.879	1.973	0.092	1.502

Since diet includes food rather than staple, so the cooking energy consumption per day per person or cooking energy consumption per person per year is a useful tool to understand the energy consumption of a region well from the Table 4-4. Based on field measurement, one research project found the daily cooking energy consumption per capita in the range of 11.5 to 49 MJ (4.2 to 17.9 GJ/capita/a). In household sector, where modern cooking energy source and equipments are used and preparation of partially cooked food is common, the specific fuel consumption per capita will lie in-between 2 to 3 MJ/day /worldenergy.rural/. The mentality, traditional value and culture cannot be excluded from the reasons of increase in cooking energy demand in developing regions. In this work, the cooking enrgy demand by developed regions consider to increase from starting period to end period of model horizon. It is assumed here that the low GDP growth rate will increase the unemployment rate and the increase in unployment will force for the cooking in house rather than to depend on outside food. It is in other word shifting of the cooking energy from commerce sector to household sector.

During the development of the cooking indicator by regions, it has been found that the useful energy demand indicator varies from minimum 0.67 GJ/capita/a in year 1990 to maximum 2.933 GJ/capita/a in 2100, i.e., from 0.74 kWh/day/capita in 1990 to 2.22 kWh/day/capita in 2100. The value 0.74 kWh/day/capita refers to the condition of the less that one warm meal per person per day that presents the situation of people to afford outside meal and high employment rate, where the cooking energy demand is included inside the commercial energy demand. Though the figure of India, China and R_NOECD region is in higher side, still people run through starvation due to extreme poverty. The highest value with 2.22 kWh/day/capita in year 2100 refers to the value of three warm meals per person per day.

The cooling useful energy indicator varies from 0.02 GJ/capita/a in 1990 to 2.6 GJ/capita/a in 2100. The cooling value can be compared with the energy demand for air-conditioning of Zaozhuang province about 0.32 GJ/capita/a in 2000 /Hongtao et al. 2003/. The heating useful energy demand varies from 16.78 GJ/capita/a in 1990 to 24.14 GJ/capita/a in 2100. The heating values can be compared to 6.48 GJ/capita/a for Zaozhuang province, which assumes per capita floor area of 25-30 m^2, space heating energy intensity of constant value (30 W/m^2), heating duration of 100 days per year and 24 hours per day for Zaozhuang province /MGZ 2003/.

The useful energy demand for cooling and heating depends on space area required per capita, heating and cooling intensity required per unit space area, insulation level of the house (conduction loss of heating and cooling), maintenance of temperature level inside the house, efficiency of the technology used, climatic condition, structural of the building construction (passive, zero-emission, body heat, etc.), material used in the building and geographical existence /worldenergy.rural/. The hot water required per capita is included inside the heating requirement per capita inside this work. The use of other electrical appliances in household sectors supported on the level of electrical gadget penetration around the regions, the degree of utilisation of electrical appliances, development and penetration of new practical use appliances in household sector. In future, developing region will utilise more appliances, compared to their present level, whereas the growth rate will be less in developed regions /worldenergy.rural/.

The maximum value of other electric appliances varies from 4.68 GJ/capita by R_OECD in 1990 to 12.13 GJ/capita in year 2100 and the minimum for India, which varies from 0.07 GJ/capita in 1990 to 1.58 GJ/capita in 2100. These values can be compared to the value of urban energy demand for lighting and electric appliances of 0.61 GJ per capita in

2000, 1.76 GJ per capita in 2020 for Zaozhuang province /Hongtao et al. 2003/ and 1.74 GJ per capita in 2000 for Beijing /Tong 2002/. Also the values can be compared with rural per capita energy demand for lighting and electric appliances of 0.27 GJ per capita in 2000, 1.17 GJ per capita in 2020 for Zaozhuang province /Hongtao et al. 2003/ and 0.85 GJ per capita in year 2020 for rural areas of Beijing /Tong 2002/.

4.3.2.4 Transport sector

Transport sector consists of transport of person and transport of goods. Therefore two indicators are defined for the transportation of person and goods, in which transport of person is related to the per capita demand of kilometer and transport of goods is related to the per GDP demand of kilometer. Demand of person-kilometer and ton-kilometer for the period 1990 and 1995 for India has been considered from the study of /Sukla et al. 2001/ and /Reddy et al. 2000/; and for China, it has been taken from /CSY 1990-1997/. It has been calibrated for periods 1990 and 1995 for R_NOECD region, and value for EU25 and R_OECD regions has been taken from PRIMES model for the same two periods. Demand of person-kilometre and ton-kilometre by regions from year 2000 to 2050 are taken from ETP model projection and calibrated till 2100 by looking towards the trend of the growth rates /Mobility 2030/, /Fulton and Eads 2004/.

Transportation demand in all regions will increase in the future, with slow growth rate in developed regions, as they are saturated by their demand and high growth rate by developing regions (see Table 4-5 and Table 4-6). Rapid population growth, increase in purchasing power, rising standard of living, booming employment rate and expanding ownership of private automobiles increase the demand of passenger kilometer in developing regions. Similarly increase in regional economy, dissimilar distribution of the natural resources, higher material demand, energy security to fullfil the gap of production and consumption disparities in a region are the causes for rise in ton-kilometer demand /eia.oiaf.enduse/ in all regions. The factors associated like: aging population, low population growth, projected low birth rate, high taxes on transportation fuels, environmental policies and high taxes levied on motorists (e.g., passenger cars in Japan are subject to nine taxes imposed on acquisition, ownership, and operation) limits energy consumption in transport sector of developed regions. The taxes, aimed at reducing oil imports, consumption, saving and securing government funds.

Table 4-5: Assumptions on Person-Kilometre demand and related indicators

Person-kilometer/capita [k Pkm/capita]					
Regions	1990	2000	2030	2050	2100
EU25	10.59	12.47	16.84	19.84	24.72
R_OECD	17.92	18.47	20.61	23.29	28.02
R_NOECD	3.53	3.54	3.97	5.31	7.51
INDIA	1.57	2.20	2.95	4.31	5.74
CHINA	1.71	2.09	5.15	9.45	12.41
World	5.08	5.35	6.43	8.21	10.17
Person-kilometer demand [billion Pkm]					
Regions	1990	2000	2030	2050	2100
EU25	4562	5520	7483	8025	8312
R_OECD	10969	12558	17393	20709	23661
R_NOECD	7744	9244	15917	24840	44187
INDIA	1337	2239	4170	6942	9921
CHINA	1954	2647	7442	13520	18122
World	26566	32208	52405	74036	104203
Average person-kilometre demand growth rate [%/a]					
Region	1990-2000	2000-2030	2030-2050	2050-2100	
EU25	1.92	1.02	0.35	0.07	
R_OECD	1.36	1.09	0.88	0.27	
R_NOECD	1.79	1.83	2.25	1.16	
INDIA	5.29	2.09	2.58	0.72	
CHINA	3.08	3.51	3.03	0.59	
World	1.94	1.64	1.74	0.69	
Person-kilometer/GDP [Pkm/€(00)]					
Regions	1990	2000	2030	2050	2100
EU25	0.6293	0.6175	0.4543	0.4012	0.3474
R_OECD	0.9350	0.8025	0.5777	0.5300	0.4591
R_NOECD	0.9354	0.9506	0.5887	0.5134	0.3930
INDIA	0.8853	0.8733	0.4607	0.4021	0.2854
CHINA	1.1018	0.5837	0.3546	0.3759	0.2761
World	0.8697	0.7778	0.5056	0.4608	0.3614

(Source: /Mobility 2030/, /Fulton and Eads 2004/)

Table 4-6: Assumptions on Ton-Kilometre demand and related indicators

Ton-kilometer/GDP [tkm/€(00)]					
Regions	1990	2000	2030	2050	2100
EU25	0.24	0.24	0.23	0.22	0.20
R_OECD	0.39	0.38	0.34	0.33	0.30
R_NOECD	0.47	0.44	0.33	0.28	0.20
INDIA	0.27	0.21	0.24	0.25	0.17
CHINA	0.55	0.34	0.27	0.26	0.18
World	0.38	0.35	0.30	0.28	0.21
Ton-kilometer demand [billion tkm]					
Regions	1990	2000	2030	2050	2100
EU25	1763	2149	3730	4416	4848
R_OECD	4543	5873	10165	12857	15315
R_NOECD	3910	4301	8794	13653	22226
INDIA	404	541	2136	4261	5776
CHINA	976	1538	5753	9421	12064
World	11596	14401	30578	44609	60229
Average ton-kilometer demand growth rate [%/a]					
Region	1990-2000	2000-2030	2030-2050	2050-2100	
EU25	1.9945	1.8557	0.8478	0.1870	
R_OECD	2.6010	1.8458	1.1815	0.3505	
R_NOECD	0.9572	2.4127	2.2240	0.9793	
INDIA	2.9722	4.6841	3.5134	0.6102	
CHINA	4.6475	4.4955	2.4970	0.4957	
World	2.1897	2.5417	1.9062	0.6023	

(Source: /Mobility 2030/, /Fulton and Eads 2004/)

4.4 Technological characterization of different sectors

4.4.1 End use sectors

The end use sectors are the final energy demand sectors those convert final energy demand to useful energy demand through the end use technologies. The end-use sectors are modeled with the end use technologies and the sectors inside this are industry, commerce, residence, transport and non-energy use as depicted in Figure 4-2. The key indicators developed in section 4.3 of chapter 4 for different useful energy demand of different sectors are the drivers for the final and useful energy demand. The sectors and their end use technologies are elaborated in the following sections.

4.4.1.1 Industry sector

The energy requirements in industry sector are categorised by three types of heats and electricity demand (see section 4.3.2.1 of chapter 4). The overall RES of industry sector is divided into four sub-RES. They are further classified as high temperature (process heat), medium temperature and low temperature heat demands. The share of different type of heats in total heat is assumed inside the model differently from starting to end period. Heat producing technologies of conventional and modern type are taken for the fulfilment of the heat demand. The heating devices considered are technologies (boilers) of solar, coal, biomass, electricity, gas (conventional and condensing), hydrogen and oil; fuel cell, district heating, heat pump based on gas and electricity. From the calculation of commissioning and decommissioning curves of the plants, the past investment has been inserted. The overview of the investment cost of new installed boilers is provided below. Biomass boiler costs 240 €(00)/kW, coal boiler costs 180 €(00)/kW, district heating technology costs 663 €(00)/kW, fuel cell 6640 €(00)/kW$_{el}$, gas heat pump 608 €(00)/kW, gas boiler 92 €(00)/kW, condensing gas boiler 113 €(00)/kW, hydrogen boiler 600 €(00)/kW, oil boiler 92 €(00)/kW and solar boiler 4830 €(00)/kW. The boiler efficiency based on energy carriers varies from 0.76 to 1. Improving efficiency of each technology with time has also been considered. Additionally, energy saving measures are modelled by the compensation with the cost, i.e., the saving measure is modelled as the increase in efficiency of the dummy processes those utilise the cost. These processes are modelled for different energy saving scenarios those can be handled in future.

4.4.1.2 Commerce sector

Commerce sector consist of agriculture, public service and commercial activity energy demand (see section 4.3.2.2 of chapter 4). It comprises of the heating, electricity and cooling energy demand fulfilment. Heat producing technologies are taken inside this sector for the fulfilment of the heat demand. The technologies considered are conventional and modern types. Heating energy demand is satisfied by fuel cell, technologies (boiler) of solar, biomass, coal, gas (conventional and condensing), hydrogen and oil. The overview of the investment cost of different boilers used in commerce sector is more or less of same techno-economic parameter like industry (see above of industry sector). For the useful cooling energy demand different technologies are modelled. They are air conditioner; heat pump based upon natural gas, solar, geothermal and district heat. The investment cost of these technologies are considered as 669 €(00)/kW for gas and electricity based heat pumps, 736 €(00)/kW for geothermal based heat pump, 702 €(00)/kW for district heat based heat pump and 775 €(00)/kW for environmental heat pumps. The efficiency figure of these heat pumps is considered as unit. Past investment has been calculated from the commissioning curve of the heat plants and cooling devices. Energy saving process has been modelled by efficiency improvement with counterbalance of cost. The saving processes are modeled for scenario analysis of the model on energy saving measures in future. This has been done for the future purpose of the different scenario analysis on saving measures.

4.4.1.3 Residence sector

Residence sector has been modelled with end use technologies that fulfil the useful energy demand of heat, electricity, cooling and cooking (see section 4.3.2.3 of chapter 4). Cooking technologies considered for cooking purpose are biogas burner, coal burner, conventional stove to use dung and biomass, electric cooker, gas tank burner, LPG burner, oil burner and solar cooker. The investment cost of various cooking technologies considered are different, e.g., biogas burner as 22 €(00)/kW, coal burner 9.5 €(00)/kW, conventional burner 5.0 €(00)/kW, electricity burner as 15.0 €(00)/kW, natural gas burner as 17.0 €(00)/kW, LPG burner as 18.0 €(00)/kW, oil burner as 16.0 €(00)/kW and solar cooker 187 €(00)/kW. Conventional cooker has very low efficiency that starts from 10% and ends at around 50%, e.g., biomass, dung, coal, kerosene, etc. LPG, natural gas, electricity and solar cooker has high efficiency and the range of efficiency considered lies in-between the values of 0.55 to 1. The investment cost of different cooking technologies is around 10% higher for developed regions compared to developing regions considered inside this study.

Different technologies are modelled for the useful cooling energy demand. They are air conditioner; heat pump based upon natural gas, environmental, geothermal and district heat. The investment cost and the efficiency of the heat pumps are taken as same of the commcerce sector (see section 4.4.1.2 of chapter 4). Heat producing technologies are modelled in this sector for the fulfilment of the heat demand. The technologies considered are conventional and modern types. Heating energy demand is satisfied by fuel cell, technologies (boiler) of solar, biomass, coal, gas (conventional and condensing), hydrogen and oil. The investment cost of biomass boiler is 950 €(00)/kW, boiler by electricity is 1260 €(00)/kW, fuel cell 6442 €(00)/kW$_{el}$, conventional gas boiler 373 €(00)/kW, condensing type of gas boiler 456 €(00)/kW, geothermal heat pump as 735 €(00)/kW, district heat radiator 181 €(00)/kW, oil boiler 403 €(00)/kW and solar boiler as 4083 €(00)/kW. The efficiency of these boilers is in the same range of commerce sector (see section 4.4.1.2 of chapter 4). The other electric demand goes towards the electricity consumption by electrical appliances in household sector.

4.4.1.4 Transport sector

Transport sector satisfies two categories of transport activity demands. One is passenger-kilometre demand for the transportation of persons and another one is the ton-kilometre demand for the transport of goods (see section 4.3.2.4 of chapter 4). Transportation of person and goods take place by various modes, i.e., transportation by road, transportation by rail, transportation by air and transportation by ship. In each medium different processes are modelled to carry out the transport of person and goods. Bus, car, motorcycle, rail and plane are considered for the transportation of person; and truck, rail, plane and ship are responsible for the transportation of goods. Each type of transport technology is modeled by different energy carriers, e.g., bus by diesel, natural gas, CNG, DME, electricity, etc. Likewise each mode of transport is modeled by different transport technology, e.g., road transport system is modeled by bus, truck, car, motor cycle, etc. Technologies operated by bio-fuel and hybrid technologies are modelled inside this work. The load factor for different modes of transport system has been regarded differently for different regions. This multiplying factor refers to the conversion factor from Vehicle-Kilometre (VKM) to Person-Kilometer (PKM) and Ton-Kilometre (TKM). The model explicitly exposed to different modal split for same type of demands and technologies. The cost for different transport technologies is considered on capacity level for some technologies and on activity level of some others. The cost of motor cycle is considerd as 46 €(00)/GJ/a, types of car are considered in the range of 1060-1889 €(00)/kVKM/a, type of rails on the range of 131-146 €(00) per kilo activity level/a, i.e, rail for person on PKM and rail for goods on TKM as the activity, cost of bus is taken as 20567-22189 €(00)/kVKM/a, cost of plane around 84 €(00)/GJ/a for person and 174 €(00)/GJ/a for transport of goods and around 170 €(00)/GJ/a for the ship that meant for the transport of goods.

4.4.1.5 Non-energy use sector

Non-energy use covers use of petroleum products such as white spirit, paraffin, waxes, lubricants, bitumen and other products but they are modelled equivalently in terms of gasoil, heavy fuel oil, liquefied petroleum gas, and naphtha. It also includes the non-energy use of coal and natural gas. Non-energy use of coal includes carbon blacks, graphite electrodes, etc. It is assumed that the use of these products is exclusively non-energy use and not accounted inside the sector-wise energy consumption.

4.4.2 Central electricity and heat production

The central heat and electricity production sector produces electricity to feed the demand by the end use sectors (as shown in Figure 4-2). The demand of electricity by each end use sector is supplied form this sector. Technologies are specified by the production of heat, electricity or even both. Production of heat is contributed by heat plants (boiler) and Combined Heat and Power (CHP) plants, whereas electricity is generated by electricity and CHP plants. This sector consists of old technologies with existing capacities, new technologies and advanced technologies. Old, new and advanced technologies are further classified based on input energy carriers. Out of these technologies some are fossil fuel based, some are hydropower technologies, some are renewable and some are nuclear-based technologies. The sector contains the modern technologies like fusion, gasification technologies (biomass, hard coal and natural gas) with and without carbon sequestration, learning technologies like integrated gasification combined cycle, combined cycle gas turbine, Molten Carbonate Fuel Cell (MOFC), Solid Oxide Fuel Cell (SOFC), wind onshore, wind offshore and geothermal heat pump; new nuclear and also the fossil technologies available at present and in future. Commissioning and decommissioning curve of the power plants are calculated till 1997 and inserted inside each regional model in the form of past investment as provided in the Annex A. The capacity bound is given for the period 1990, 1995 and 2000 for some technologies and activity bound on some other technologies.

The investment cost for the technologies based on biomass is considered in-between 1648 to 2770 €(00)/kW, biogas around 1534 €(00)/kW, molten carbonate fuel cell 9391 €(00)/kW, solid oxide fuel cell 7669 €(00)/kW, wind technologies in the range of 1015-1245 €(00)/kW, fusion 3478 €(00)/kW, lignite 1175 €(00)/kW, waste within the range of 1240 to 2312 €(00)/kW, solar technologies in-between 4878 to 5072 €(00)/kW, Geothermal technologies around 4982 €(00)/kW, hydro in the range of 1981 to 3556 €(00)/kW, natural gas technologies in the range of 247 to 1094 €(00)/kW, oil within 247 to 766 €(00)/kW and coal around 928 to 1391 €(00)/kW. For some technologies the investment cost with respect to time learns exogenously, e.g., molten carbonate fuel cell, solid oxide fuel cell, wind onshore, wind offshore, fusion technology, solar PV, solar thermal, IGCC, CCGT, geothermal, hydro, nuclear, etc. The efficiency of the technologies based on type of fuels and also type of technologies (CHP and electricity plants) is different. The investment cost, fixed operating and maintenance cost and efficiency of few electricity and CHP plants are provided in Table 4-7. The technology data are taken from Enquete-Kommission /Enq.-Kom./, TIMES Germany model and IER data bank.

Table 4-7: Characteristic of some electricity and CHP plants

Technology	Abbrev.	Inv. Cost [€(00)/KW]	Fixed O&M Cost [€(00)/KW]	Effic. [Frac.]
New Coal Power Plant, Condensing	WECOLN1	928	64	0.41
New Coal Power Plant, CHP	WECOLN2	1185	52	0.85
New Coal Power Plant, IGCC	WECOLN3	1079	22	0.46
New Coal Power Plant, IGCC with CO2 Sequestration	WECOLN4	1391	36	0.42
New Gas Turbine	WEGASN1	399	19	0.39
New Gas Based CHP Plant	WEGASN2	598	30	0.81
New Gas Based Combined Cycle Plant	WEGASN3	426	20	0.53
New Gas Based CC Plant with CO2 Sequestration	WEGASN4	559	21	0.50
Oil steam plant	WESTEEO	1337	53	0.43
Molten carbonate fuel cell	WEMCFCN	6391	143	0.85
Solid oxide fuel cell	WESOFCN	7669	109	0.76
New Nuclear Power Plant, EPR	WENUCN1	1498	23	0.35
New Nuclear Power Plant, HTR	WENUCN2	1505	30	0.82
New Solar Power Plant, Solar Thermal	WESOLN1	4879	97	1.00
New Solar Power Plant, Solar PV	WESOLN2	5072	101	1.00
Existing Hydro Power Plant	WEHYDE1	3290	65	1.00
New Medium Hydro	WEHYDN5	4008	60	1.00
New Small Hydro	WEHYDN6	3912	58	1.00
New Wind Power Plant, On-Shore	WEWINN1	1015	22	1.00
New Wind Power Plant, Off-Shore	WEWINN2	1245	37	1.00
New Waste Power Plant	WEWASN1	2312	115	0.33
New Condensing Turbine CHP / Biomass	WEBION3	2198	219	0.85
Electricity Plant by Biomass	WEBION2	2072	155	0.46
New Biogas Plant, CHP	WEBIGN1	1534	30	0.88

4.4.3 Biogas and bio-fuel production

Both biogas and bio-fuel (bio-diesel) production are modelled inside this study. Biogas is used in developing regions in the cooking sector and also used for electricity and heat production. Bio-diesel is produced from biomass and consumed in transport sector only. Also methanol and ethanol are produced from biomass and consumed in transport sector. The process specific data for the production of the biogas and bio-fuels are provided in the Annex A. The investment cost of bio-fuel process lies in-between 15.85 to 44.39 €(00)/GJ/a and efficiency lies intermediate 0.7 to 0.9.

4.4.4 Synthetic fuel production

Methanol and ethanol are the two types of synthetic fuels used in transport sector, which are modelled inside this study currently. Brazil and Sweden use more ethanol in transport sector. Market share of ethanol in their transport sector retains a high value. The share of methanol in transport sector is very low and restricted to below 1%, as it has the adverse effect to the health condition like blindness problem due to contamination of the methanol.

The technology specification data on synthetic fuel producing technologies are provided in the Annex A. Two types of technologies are modelled for the production of synthetic fuels from coal and natural gas, e.g., without and with CO_2 sequestration. Qatar, Malaysia, South Africa and China are the biggest users of the synthetic fuels produced from coal. South Africa is making around 200 kilo barrels of gasoline and diesel a day from coal. The cost of making a barrel of synthetic fuel is approximately $35 a barrel, including the infrastructure and labour force /faqsynthetic/. Other study also reflect the low price for production of DME and diesel, i.e., in the range of $27 to $36 per barrel from coal with price of $0.5/GJ /Celik et al./.

4.4.5 Hydrogen (H_2) production

In the context of energy systems, hydrogen is best thought of an energy carrier, more akin to electricity and heat than the fossil fuels that extracted from the earth’s crust. It is a high quality secondary energy carrier and thus has to be produced from primary and secondary energy sources such as coal, oil, gas, biomass and electricity. Hydrogen is the lightest, abundant and high quality secondary energy carrier. Potential use of this energy carrier may takes place during the scarcity of the fossil fuel carriers like gas, oil and coal. Production and consumption of hydrogen is limited at present time, as it is not able to compete techno-economically with fossil fuels /Lipman 2004/, /Krewitt, Schmid 2004/. It scarcely contributes anything to global warming and local pollutions. Its supply is virtually unlimited. Fuel cells and other technologies using hydrogen as the input energy source will play a major role in transformation towards more flexible, less vulnerable, distributed energy system that meets the energy need in a cleaner, more efficient and cost-effective way /Lipman 2004/.

Hydrogen can be produced in molecular form by various ways and from different sources. Hydrogen is modeled inside this work and produced from hard coal, natural gas, biomass and electricity. Hydrogen production takes place from different processes like biomass gasification, coal partial oxidation with and without CO_2 sequestration; gas steam reforming with and without CO_2 sequestration; and electrolysis. It is going to various end use sectors like residence, industry, commerce and transport sector. The techno-economic specification on hydrogen producing technologies is given in the Annex A. The investment cost of different processes lies within 10.34 to 63.26 €(00)/GJ/a and the efficiency remains within 0.49 to 0.66.

4.4.6 Carbon Capture and Storage (CCS)

There are several ways to bring down the CO_2 growth in the atmosphere: by reducing the energy use, energy use in efficient way, eco-efficient technology development, use of low-carbon and carbon-free fuels and use of fossil fuels with carbon capture and storage option, and development of carbon sink. Carbon dioxide sinks are the natural process of sequestration and it includes the development of the forest (some time forest acts as carbon source, when carbon from the soil is released), rapid development of phytoplankton or microbial inside the sea (immersion of hematite or iron sulphate inside water), soil (tilling, crop rotation, increasing humus level, etc.) /wikipedia.carbon/ and stored in a safety vessel. Out of all the alternatives, carbon captures and storage is brought to the global forefront. In this mechanism CO_2 is captured from the flue gas of burning coal and transported for storage purpose. The carbon dioxide can be captured by large amount from the production side by amine based solvents, pressure and temperature swing absorption, gas separation membrane, cryogenics, coal gasification, oxyfuel combustion and hydroxide use /wikipedia.carbon/.

The captured carbon dioxide can be deposited inside the depleted coal mines (enhanced coal bed methane recovery), depleted oil fields (enhancement of oil recovery), depleted gas fields (methane recovery) and dumping in deep ocean layer. The cumulative storage of CO_2 by regions of different storage options (coal, oil, gas, onshore and offshore saline formations) is taken from the work of /Dooley et al. 2004/ is provided in the Table 4-8.

Table 4-8: Carbon dioxide storage capacity by sources

Carbon dioxide storage capacity [Mton]						
Regions	**Coal**	**Oil**	**Gas**	**Onshore**	**Offshore**	**Total**
R_OECD	91667	11000	51333	3938000	1635333	5728433
R_NOECD	58667	95333	627000	1092667	2009333	3884100
EU25	3667	0	7333	106333	11000	128333
India	7333	0	7333	187000	187000	385000
China	14667	3667	7333	330000	33000	388667

(Source: /Dooley et al. 2004/)

The cost of storage is taken from /Dooley et al. 2004/, /IEA/AIE 2004/, which varies from 45 €(00)/ton to 100 €(00)/ton of CO_2, in various storage devices for the year 2000. The value of storage cost for 2030 is taken as half of the value of 2000 and for periods in-between 2000 and 2030, they are interpolated (see Table 4-9) and the cost of 2030 remains same till 2100. The cost of storage depends on distance of transportation for storage, mode of transportation, geological landscape, etc.

Table 4-9: Carbon dioxide storage and the cost per unit carbon dioxide storage

Region	Cumulative storage capacity of CO_2 [Mton]	Carbon dioxide storage cost [€(00)/ton]									
		1990	2000	2005	2010	2015	2020	2025	2030	2050	2100
R_OECD	5728433	51	51	50	45	40	35	30	26	26	26
R_NOECD	3884100	52	52	51	46	41	36	31	26	26	26
EU25	128333	48	48	46	45	40	34	29	24	24	24
India	385000	54	54	54	48	43	38	32	27	27	27
China	388667	48	48	48	47	41	35	30	24	24	24

(Source: /Dooley et al. 2004/, /IEA/AIE 2004/)

4.5 Reserves and resources

Resources are defined as "concentration of naturally occurring solid, liquid and gaseous materials inside or on the earth's crust in such a form that economic extraction of the commodity from the concentration is currently or potentially feasible" /USA.mining 1980/. From geological point of view, a resource is categorised into identified and undiscovered. Identified resources are those, whose location, grade, quality and quantity are already known or can be estimated in a specific geological condition. With varying degree of geological uncertainty, identified resources can be divided into demonstrated (measured + indicated) and inferred[3]. Undiscovered resources are quantities anticipated to exist under analogous geological condition with different degree of probability.

The production, consumption, reserve and resource are the indicators for the sustainability on energy carriers by the regions of the TIMES G5 model to predict the stand of the regions on energy availability. The development of the indicators like consumption per production and reserve by production reflects the level of import of the energy carriers and the sustainability of the energy carrier on resource ground for the future. These indicators are provided in the Table 4-10 for different energy carriers and regions of the year 2000. For example India produces 20 Mtoe of coal in year 2000, consumed 22 Mtoe of coal and has resource and reserve of 1200 Mtoe then the ratio of consumption per production is 1.1 and reserve and resource by production is 60.

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[3] Inferred resources are based on an assumed continuity beyond measured and (or) indicated resources, for which there is geological evidence.

Table 4-10: Indicators for resource, production and consumption of regions

Energy carrier	Hard coal	Lignite	Crude oil	Natural gas
EU25				
Consumption/Production	1.32	1.00	3.26	1.96
Resv.&Reso./Production	1168.33	722.22	48.24	436.32
R_OECD				
Consumption/Production	0.95	1.00	1.73	1.07
Resv.&Reso./Production	1056.76	1943.01	401.78	876.57
R_NOECD				
Consumption/Production	1.23	1.00	0.46	0.76
Resv.&Reso./Production	4529.31	5726.24	224.97	1795.00
INDIA				
Consumption/Production	1.08	1.00	3.13	1.07
Resv.&Reso./Production	945.99	4199.91	50.24	245.83
CHINA				
Consumption/Production	0.94	1.00	1.78	0.96
Resv.&Reso./Production	751.46	4437.34	49.38	527.02

4.5.1 Reserve and resource overview on India

India has huge potential of coal, lignite, hydropower and visualize the resource deficiency of natural gas, crude oil and uranium in future. Its coal reserve will continue to last for another 250 years, at the present rate of consumption. The deficiency of crude oil in transport sector has been occurred already and is a net importer of crude oil and refined oil products. The resource and reserve potential of hard coal is 139.79 Gtoe /ISY 1999/, lignite is 21.65 Gtoe /ISY 1999/, crude oil is 1.72 Gtoe /ISY 1999/, natural gas is 5.67 Gtoe /ISY 1999/ and uranium is 1.604 Gtoe /worldenergy.India/. The reserve and resource figures of energy carriers collected by sources during this work are presentated in Table 4-11.

Coal is important and abundant fossil fuel in India and has a leading role in world coal reserve, secure the position behind the United States, Russia and China, and accounts about 7.5% of the world’s annual coal production. Not only India is third in coal reserves but also world’s third-highest coal consuming and producing country, again behind China and the United States, and accounts for about 8% of the world’s annual coal consumption, which accounts nearly 55% of the country’s energy need. Out of total coal production, share of open pit or opencast mining is around 81% and underground mining is 19%. Nearly three quarters of India’s electricity and two-thirds of its commercial energy comes from coal and the demand of coal has been steadily increasing over the past decade /coal.IEA.india/, /coal.nic.in/.

Even though India is able to satisfy most of its country's demand through domestic production, less than 5% of its reserves are cooking coal used by the steel industry. As a result, India's steel industry imports cooking coal, mainly from Australia and New Zealand, to meet about 25% of the its annual needs /coal.nic.in/. Coal Bed Methane, commonly known as coal gas, is a high quality natural gas absorbed in coal seams. It is also a greenhouse gas and 20 times more potent than carbon dioxide. India has around 1533.22 billion cubic metres of coal bed methane as resource /static.teriin/.

Nearly 30% of India's energy needs are met by oil, and more than 60% of which is imported. The Indian government is encouraging increased production of petroleum to reduce its dependence on imported oil. India is becoming a major global market for petroleum products especially for kerosene and distillate fuel oil. Consumption of petroleum products rose from 57 million tons in 1991-1992 to 107 million tons in 2000, and forecasts for year 2005 put market volume at 163.8 million tons. The India Hydrocarbon Vision 2025 report estimates future refinery demand at 368 million tons by 2025 /petroleum.nic.in/.

Table 4-11: Reserves and resource of India

Potential by energy carriers						
Carriers	Source	Unit	Reserve	Resource	Rev.&Res.	Model
Hard Coal	/ISY 1999/	Bton	68.05	222.89	290.94	
Hard Coal	/ISY 1999/	Gtoe	32.48	106.39	138.87	139.79
Hard Coal	/indiaworldenergy/	Bton			211.59	
Hard Coal	/indiaworldenergy/	Gtoe			100.99	
Lignite	/ISY 1999/	Bton	1.90	90.02	91.92	
Lignite	/ISY 1999/	Gtoe	0.44	21.06	21.51	21.65
Lignite	/indiaworldenergy/	Bton	34.17			
Lignite	/indiaworldenergy/	Gtoe	8.00			
Crude Oil	/ISY 1999/	Bton	0.78	4.65	5.43	
Crude Oil	/ISY 1999/	Gtoe	0.80	4.75	5.55	1.72
Crude Oil	/coal.IEA.india/	Gtoe	0.76			
Natural gas	/ISY 1999/	Tcm	0.69	0.74	1.42	
Natural gas	/ISY 1999/	Gtoe	0.59	0.63	1.22	5.67
Natural gas	/coal.IEA.india/	Tcm	0.65			
Natural gas	/coal.IEA.india/	Gtoe	0.56		0.56	
Thorium	/world-nuclear/	Kton			290.00	
Thorium	/world-nuclear/	Mtoe			4060.00	
Thorium	/coal.IEA.india/	kton			363.00	
Thorium	/coal.IEA.india/	Mtoe			5082.00	
Uranium	/DOE.India/	kton	34.00			
Uranium	/DOE.India/	Mtoe	476.00			
Uranium	/worldenergy.india/	kton			114.62	
Uranium	/worldenergy.india/	Mtoe			1604.61	1604.61

Natural Gas is a vital component of energy supply at present and also for future. The production of natural gas during 1998-1999 was around 75 Million Metric Standard Cubic Meters per Day (MMSCMD). Out of total natural gas, 60% of the natural gas is produced along with crude oil and the rest as free gas. Natural gas has experienced the fastest rate of increase than any fuel in India's primary energy supply. It supplies about 7% of India's total commercial energy and the demand is growing at about 6.5% per year /petroleum.nic.in/. To meet the gap of supply and demand, the Government have taken steps and signed Memorandum Of Understanding (MOU) with Oman and Iran and also looking to import from Bangladesh and Myanmar. Also India is planning to import LNG from Middle East region in future through the pipeline for future demand of natural gas.

The seismic data reflects that there is possible evidence of widespread gas hydrate occurrence in the proposed lease blocks (costal belt) and there is a large prospect of gas hydrates estimated to be 6 trillion cubic meter in between India and Myanmar inside Andaman Sea /aapg.hydrates/. The government of India taking initiation to extract the gas from gas hydrates to feed its growing energy demand.

4.5.2 Reserve and resource overview on China

China has huge potential of coal, lignite, natural gas, uranium, hydropower and visualize the resource deficiency of natural gas and crude oil. China's coal reserve will continue to long time period at the rate of present consumption. The resource and reserve potential of hard is 525.15 Gtoe /ISY 1999/, lignite is 54.95 Gtoe /ISY 1999/, crude oil is 7.46 Gtoe / ISY 1999/, natural gas is 14.81 Gtoe /ISY 1999/ and uranium is 24.78 Gtoe /worldenergy.china/. The reserve and resource figures of different energy carriers are collected from various studies or sources and demonstrated in Table 4-12.

Energy consumption in China heavily depends on coal and it accounted for over 76% of primary energy supply (excluding combustible renewables and waste) and over 62% of the final commercial energy consumption in year 1996. Three quarters of the electricity generated is out of coal. China's coal industry is largest in the world and between 1980 and 1996, production increased more than doubled from 620 million tones to 1,397 million tones /china.daily 1999/.

With respect to coal reserve, China secured the position behind USA and Russia, and has 11% of the world's proven recoverable reserves with 114.5 billion tonnes, in which 75% is classified as bituminous, 12% anthracite and 13% lignite. Steam coal accounts for 83% of the total, with cooking and gas coals of 17%. Open cut mining contributes approximately 5% of the total coal output. The average depth of all underground mines is estimated at 330 metres, although some mines are at a depth of 1,000 metres.

Coal Bed Methane, commonly known as coal gas, is a high quality natural gas absorbed in coal seams. China has significant volumes of coal-bed methane located in the central and eastern regions of the country and accounted as 35000 billion cubic metres at a depth of 2,000 metres /Schultz 1998/.

Table 4-12: Reserves and resource of China

Potential by energy carriers						
Carriers	Source	Unit	Reserve	Resurce	Rev.&Res.	Model
Hard Coal	/ISY 1999/	Bton	62	764	826	
Hard Coal	/ISY 1999/	Gtoe	39	481	521	525.15
Lignite	/ISY 1999/	Bton	52	135	187	
Lignite	/ISY 1999/	Gtoe	15	39	54	54.95
Total Coal	/zdt.com.cn/	Bton			1000	
Crude Oil	/chinaonline.energy/	Bton	2	12	14	
Crude Oil	/chinaonline.energy/	Gtoe	2	12	15	7.64
Crude Oil	/ISY 1999/	Bton	3	3	7	
Crude Oil	/ISY 1999/	Gtoe	3	3	7	
Natural gas	/chinaonline.energy/	Tcm	2	44	46	
Natural gas	/chinaonline.energy/	Gtoe	2	38	40	
Natural gas	/ISY 1999/	Tcm	2	5	6	14.81
Natural gas	/ISY 1999/	Gtoe	1	4	5	
Uranium	/ISY 1999/	kton	72	1842	1914	
Uranium	/ISY 1999/	Mtoe			26796	
Uranium	/worldenergy.china/	kton	70			
Uranium	/worldenergy.china/	Mtoe	980			
Uranium	/worldenergy.china/	kton			1770	
Uranium	/worldenergy.china/	Mtoe			24780	24780.00

China’s significant oil exploration took place in the Lachunmia field in 1939 and an extensive exploration programme for self-sufficiency of oil was launched in 1950s. China is the world’s sixth largest oil producer and produced 3.2 million barrels of oil per day in year 1997 mainly for its internal consumption. Since 1993, China become a net importer of crude oil and is in search of new reserves to satisfy her demand. The future target is the remote Tarim Basin in the northwest corner of the country and the offshore areas in the South China sea. China exported more than 7 million tonnes of crude oil in 1999 /DOE/EIA/.

China is currently the sixth greatest crude oil producing country and accounts for about 4.8% of the world’s total annual crude oil production. China’s growing demand for oil, more than 5.5% per year has greatly outstripped its domestic production capabilities and made a net oil importer. Country is already the third greatest oil consuming country (behind the United States and Japan) and accounts about 6.5% of the world’s total annual oil consumption. China is looking to import the oil in future from Russia /DOE.china/.

China was one of the first countries in the world to utilized natural gas towards first century, when gas was produced and transported in bamboo pipes. However, despite its promising initiation, the natural gas industry did not experience rapid growth compared to rest of the world. Out of total gas consumption in year 1999, the chemical sector, mostly fertilizer production, accounted for 39%, followed by oil and gas field's own uses (27%), gas distribution inside the city (13%), power and heat production (10%), industry sector excluding fertilizer (7%), and transport and distribution losses (4%) /IEA.chinagas 2002/. Natural gas production in China has increased from 3.4 billion cubic metres in 1971 to 22.7 billion cubic metres in year 1997, it still remains a marginal fuel within the Chinese energy balance and under-utilized relative to the total resource /WEO 1998/.

China has interest on import of LNG as the demand of natural gas increases rapidly, due to installation of new gas based power plants, conversion of oil power plants to gas and heavy demand by residential sector of southeastern costal region. In this context, Guangdong sheng has started a project to build six large gas fired power plants and to convert an existing 1,800 MWe of oil-fired power plants to LNG fuel. Already two LNG terminals have been approved for construction in Guangdong and Fujian sheng /DOE.china/.

Most oil shales are fine-grained sedimentary rocks containing relatively large amounts of organic matter from which significant amounts of shale oil and combustible gas can be extracted by destructive distillation. The operation of heating retorts for processing the oil shale and commercial extraction of oil shale was carried out in the Fushun region of China in-between the years 1920-1930, in year 1992 under the management of the Fushun Bureau of Mines. Its 60 retorts annually produce 60000 tonnes of shale oil to be sold as fuel oil, with carbon black as a by-product /worldenergy.shale/. The oil content of the low-grade oil shale is less than 4.7% by weight and upper grade is greater than 4.7% and can go as high as 16% but it has been reported that the average oil contain of Chinese shale oil is 7-8%, which would produce 78-89 litres of oil per tonne of oil shale (assuming a 0.9 specific gravity) /worldenergy.shale/.

4.5.3 World potentials of different energy carriers

The resource and reserve potential of different energy carriers by region has been collected as given in Table 4-13. It differs by different sources as the method of calculation; assumptions and aggregation of fuel carriers are different from one author to another. SAUNER has highest projection out of all sources due to the consideration of conventional and unconventional sources. For the case of crude oil, it includes crude oil and Natural Gas Liquid (NGL) as conventional source, and oil shale, tar sand, extra heavy oil and natural bitumen (oil sand) non-unconventional source. In natural gas reserve and resource calculation, it includes natural gas and natural gas liquid in conventional source, and coal bed methane, tight gas, gas hydrates and aquifer gas in unconventional sources. For the hard coal and lignite calculation, it takes hard coal and brown coal. In its total amount calculation of each energy carriers, it includes some additional occurrences of values. Out of many resource and reserve values available for modelling purpose for TIMES G5 model, the highest values are choosen as keeping in mind that the technology development for extraction and exploration in future may locate more resources.

Table 4-13: Reserve and resource potential of energy carriers by regions

Hard coal by various sources [Gtoe]							
Sources	World	EU25	R_OECD	R_NOECD	India	China	State of Information
/SAUNER 2000/	3672.10	320.50	700.50	2251.10	75.10	324.90	1996/1999
/DOE/EIA 2001/	722.00						2000/2001
/WETO 2003/							1996
/WEC 2003/	549.48	16.44	189.56	207.09	66.06	70.33	2002
/ISY 1999/					138.87	520.60	1998
/BP 2004/	381.52	44.83	131.63	98.78	60.56	45.72	2003
Model Assump.	3689.18	322.95	705.97	1995.32	139.79	525.15	1988
Lignite by Various Sources [Gtoe]							
/SAUNER 2000/	773.10	24.10	201.60	518.00	1.30	28.10	1996/1999
/DOE/EIA 2001/							2001
/WETO 2003/							1996
/WEC 2003/	115.84	12.50	54.01	33.97	1.73	13.64	2002
/ISY 1999/					21.51	54.27	1998
/BP 2004/	342.07	62.18	132.75	107.22	1.47	38.44	2003
Model Assump.	775.65	24.47	202.42	472.17	21.65	54.95	1988
Gas by Various Sources [Gtoe]							
/SAUNER 2000/	2333.40	82.10	563.80	1576.60	54.70	56.20	1996/1997
/O&J 2003/	148.16						2004
/WETO 2003/	416.65						1996
/Cedigaz 2004/	154.29						2004
/ISY 1999/					5.55	14.66	
/BP 2004/	151.52	2.81	15.44	130.97	0.74	1.57	2003
Model Assump.	2349.17	83.02	569.74	1675.92	5.67	14.81	1988
Crude Oil by Various Sources [Gtoe]							
/SAUNER 2000/	881.71	8.68	341.52	514.06	1.52	16.03	1993/1996/1997
/O&J 2003/	399.13	9.81	68.68	311.33	2.18	7.14	2004
/WETO 2003/	612.00						1996
/O&GJ/	173.42						2003
/World Oil/	143.97						2003
/BP 2004/	157.26						2003
/OPEC 2003/	120.82						2003
/USGS 2000/	360.00						1996
/ISY 1999/					1.42	6.34	1998
/BP 2004/	156.09	1.16	11.02	139.93	0.76	3.22	2003
Model Assump.	911.04	9.95	349.00	542.72	1.72	7.64	1988

(Note: SAUNER projection on reserve and resource of fuels comes from many sources)

4.5.4 Supply cost curve of reserve and resource

The supply-cost function demonstrates economic extraction of a resource under specified geographical and geological condition with existing technological limitation. It is an ultimate product for availability assessment, where discrete reserves and resources quantities are cumulatively arranged in an increasing order of extraction cost. Production inevitable depletes the reserves and extinguishes the deposit, while successful exploration of new reserves is required to satisfy the energy demand. The exploration and conversion of resource into reserve is accomplished by technological improvement, which is the fundamental component for lowering of extraction cost.

The cost-potential curve of energy carriers are based on few default cost curves adopted from /Rogner 1997/, /Adelman 1993/ and /Rogner 1990/ and technological improvement has been reflected by reduction of extraction cost by 0.5% per year. In supply-cost graph, the width of histogram represent the amount of energy in EJ extracted and the height expresses the cost of extraction in €(00)/TJ, which is the average value of the whole model period, i.e., from 1990 to 2100. The behaviour of the extraction cost with respect to extraction amount can be easily realised from the given figures.

Production cost of any energy carrier is highly variable depending on geographical, geological and physical characteristics. For the case of crude oil and natural gas, it depends upon the depth and flow rate of oil, which again depends on physical features like reservoir pressure, permeability, porosity, and water saturation. Major cost development for the extraction site is utilised as investment cost that depends heavily on depth of extraction, sometimes it increases exponentially /DeLuca 1998/ but in other hand, higher flow rate reduces the extraction cost per unit of energy extracted.

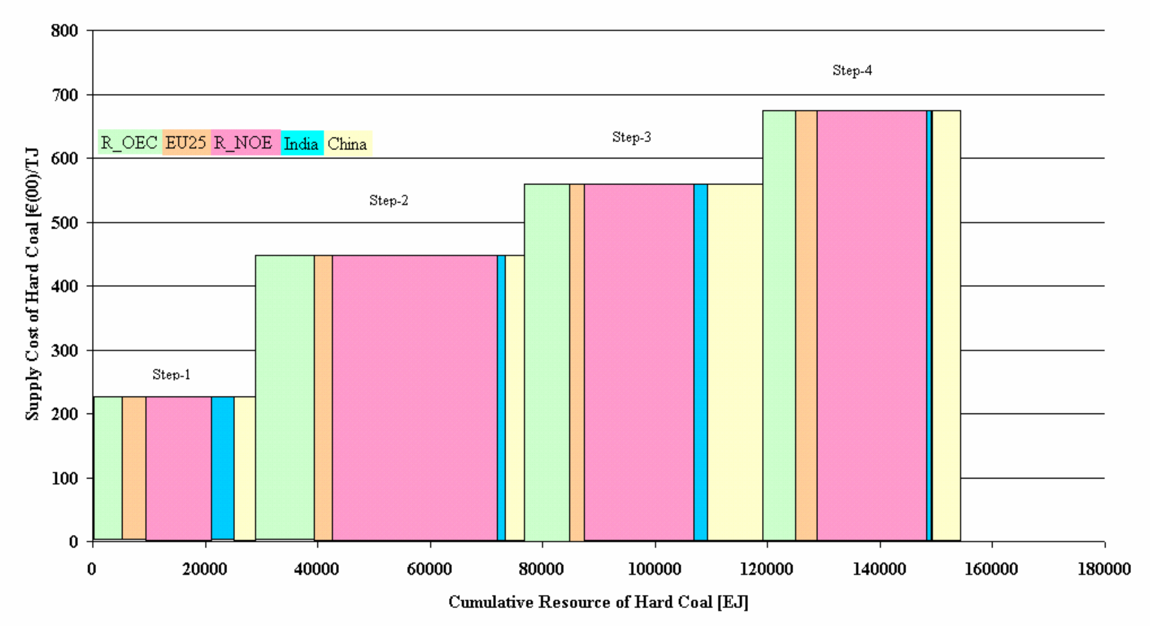

Figure 4-3: Supply-cost curve of hard coal with starting year 1988

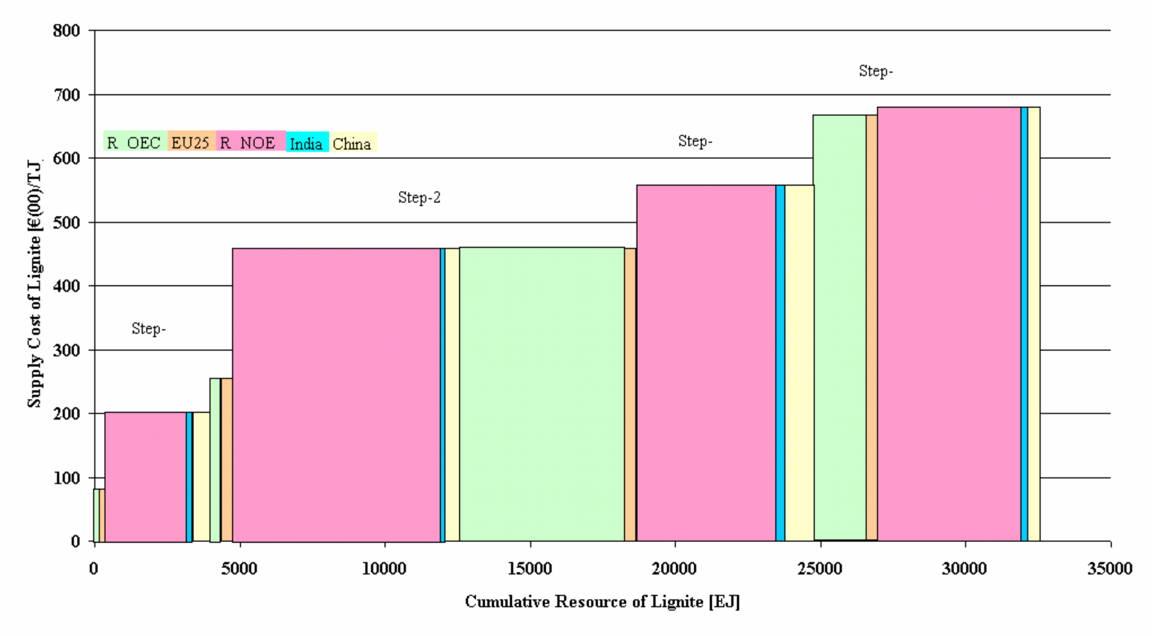

Figure 4-4: Supply-cost curve of lignite with starting year 1988

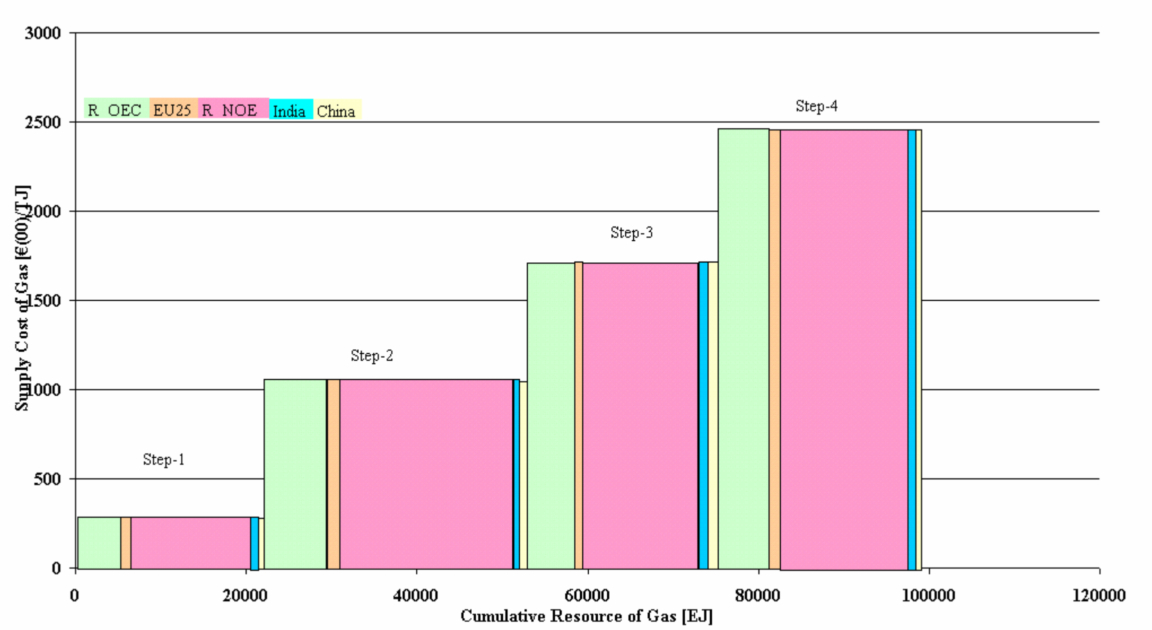

Figure 4-5: Supply-cost curve of natural gas with starting year 1988

Extraction cost of crude oil (Figure 4-6) and natural gas (Figure 4-5) are highly variable over time due to the bell shaped production function. The cost of production is around two times and more than two time for natural gas and crude oil in the last phase compared to its previous. The extraction cost of crude oil ranges in-between 0.1 to 1.4 €(00)/GJ and natural gas within 0.3 to 2.5 €(00)/GJ. Out of the supply-cost curves, it can be concluded that extraction cost of hard coal (Figure 4-3) and lignite (Figure 4-4) does not show the drastic change like natural gas and crude oil towards their last phase of extraction.

The extraction cost of hard coal ranges in-between 0.21 to 0.68 €(00)/GJ and lignite in-between 0.07 to 0.68 €(00)/GJ. But the average import price of Germany within last 15 years for hard coal, lignite, natural gas and crude oil are respectively 1.57 €(00)/GJ, 1 €(00)/GJ, 3.32 €(00)/GJ and 4.92 €(00)/GJ. From these given values, it could be easily imagine that how the import price and extraction cost has large gap. The major difference comes from the points of profit by the company and tax imposed by the government. As this model is optimisation model of the world resources, therefore the tax and profit is not included for any energy carriers. The extraction cost and the transport cost between regions are taken from SAUNER /SAUNER 2000/. The approximate amount of cumulative extraction of hard coal, lignite, crude oil and natural gas from 1988 to 2000 of whole world is 24131, 4596, 43658 and 23755 Mtoe respectively.

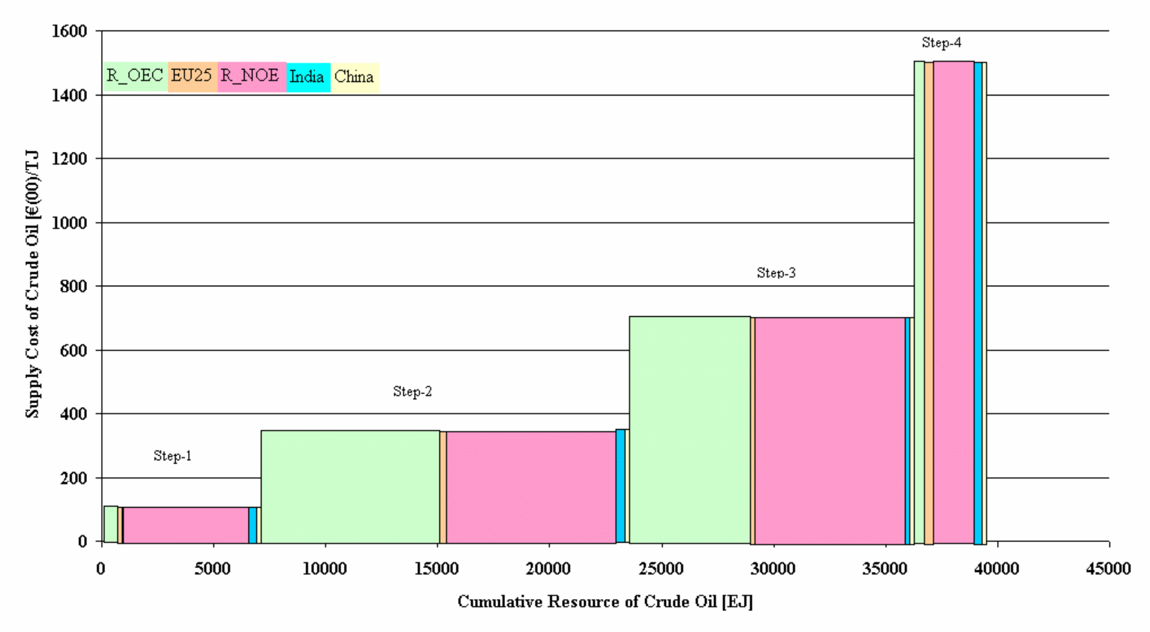

Figure 4-6: Supply-cost curve of crude oil with starting year 1988

4.5.5 Inter-regional exchange and transport cost of energy carriers

Transport cost of energy carriers play a major role in national and regional energy infrastructure development, future power generation framework, emission strategy and national energy policy development. As transportation cost depends to a great extent on distance of transportation, some times the transport cost is greater than the extraction cost of the energy carrier. For this reason some countries import the energy carriers rather than to use its own products in some parts of its regions, e.g., south east region of China use coal imported from Australia rather to use the coal extracted from north part of China.

Table 4-14: Transport cost of energy carriers

Unit transportation cost of crude oil (€(00)/PJ)						
Regions		EU25	R_OECD	R_NOECD	India	China
	Cities	Rostock	New York	Santosh	Mumbai	Shanghai
EU25	Rostock		252573	462313	293419	383153
R_OECD	New York	252573		367022	539351	515178
R_NOECD	Santosh	462313	367022		621674	839683
India	Mumbai	293419	539351	621674		227452
China	Shanghai	383153	515178	839683	227452	
Unit transportation cost of natural gas (€(00)/PJ)						
Regions		EU25	R_OECD	R_NOECD	India	China
	Cities	Rostock	New York	Santosh/Siberia	Mumbai	Shanghai
EU25	Rostock		2143044	1487543	2489611	3250986
R_OECD	New York	2143044		3114122	4576299	4371195
R_NOECD	Santosh	1487543	3114122		5274801	7124565
India	Mumbai	2489611	4576299	5274801		1929889
China	Shanghai	3250986	4371195	7124565	1929889	
Unit transportation cost of coal (€(00)/PJ)						
Regions		EU25	R_OECD	R_NOECD	India	China
	Cities	Rostock	New York	Santosh	Mumbai	Shanghai
EU25	Rostock		175197	320683	203530	265773
R_OECD	New York	175197		254585	374120	357352
R_NOECD	Santosh	320683	254585		431224	582445
India	Mumbai	203530	374120	431224		157772
China	Shanghai	265773	357352	582445	157772	
Unit transportation cost of petroleum products (€(00)/PJ)						
Regions		EU25	R_OECD	R_NOECD	India	China
	Cities	Rostock	New York	Santosh	Mumbai	Shanghai
EU25	Rostock		414220	758194	481207	628370
R_OECD	New York	414220		601916	884535	844891
R_NOECD	Santosh	758194	601916		1019546	1377079
India	Mumbai	481207	884535	1019546		373021
China	Shanghai	628370	844891	1377079	373021	
Unit transportation cost of LNG (€(00)/PJ)						
Regions		EU25	R_OECD	R_NOECD	India	China
	Cities	Rostock	New York	Santosh	Mumbai	Shanghai
EU25	Rostock		1428696	991695	1659741	2167324
R_OECD	New York	1428696		2076081	3050866	2914130
R_NOECD	Santosh	991695	2076081		3516534	4749710
India	Mumbai	1659741	3050866	3516534		1286593
China	Shanghai	2167324	2914130	4749710	1286593	

Ten energy carriers are modelled inside the inter-regional exchange sector; they are hard coal, crude oil, natural gas, liquefied natural gas, electricity, diesel (gasoil), petrol, liquefied petroleum gas, kerosene and hydrogen. Out of ten energy carriers, eight energy carriers are opened for trading purpose and rest two (H_2 and LNG) have not opened for trading. The transport cost has been taken and recalculated with the help of different source, i.e., /SAUNER 2000/, /hm-usa/ and /usembmal/.

Internal regions generated in TIMES are interconnected by trading of energy carriers, in which one region can import or export energy carriers from other regions, to meet its requirement. The help of /SAUNER 2000/ transportation data and the distance between trading centres calculate transport cost of hard coal, natural gas, LNG and crude oil. Rostock, New York, Santosh, Mumbai and Sanghai are regarded as the trading centres for the regions EU25, R_OECD, R_NOECD, India and China respectively and the straight distance between two trading centres are taken as an indication for the transportation length between them. The selection of the trading centers has significant effect on the regional energy system for the transport cost, e.g., EU25 imports major gas from Russia in which the trading center is Siberia. When Santosh is selected as the trading centre, EU25 did not import natural gas from R_NOECD region. Therefore inside this study for natural gas import and export for EU25, two trading centres have been created in R_NOECD region, i.e., Santosh and Siberia. Transport cost of crude oil and oil products are different and the transport cost of petroleum products taken are 1.64 times higher than the crude oil transport /OPEC 2004/.

Thought transport cost has been modelled inside the study for inter regional transport of goods and energy carriers but still it is ambiguous from the regional planning point of view as the trading of a region is not confined at one place of a region rather it is diversified locations inside a region. Also in this five regional global energy model, whole world is divided into five regions, where it is hard to locate the trading centres within many dispersed nations united to formulate one region. The calculation of transport cost is an approximation and quite away from the real value as the transport distance plays a major role on it. The transport cost in-between regions of energy carriers are provided in Table 4-14.

5 Scenario Formulation and Results

5.1 Scenario description

Scenarios are like storylines to foretell the future within a possible range of existence. Multiple scenarios represent the broad range of possibilities /worldenergy.scenario/, which is created from various flexibilities with the variation like; change in projection of population, GDP, energy efficiency, phase-out of fossil and nuclear energy, diffusion of technologies on various learning aspects, reduction of global and local environmental problems, implementation of investment funds, policy implication, subsidy, inclusion of external cost, CO_2 trading, etc. Thus the formulation of scenarios depends on the modeler's field of interest, for what the scenarios will be developed and tested. In this work the formulation of the base case, the restriction of the carbon concentration in the atmosphere and different learning scenarios have been studied those are provided below.

5.1.1 Base case

TIMES G5 global model consist of five regions (see chapter 4.2). The countries inside each region are provided in the Annex A. Though the nations inside the EU25, R_OECD and R_NOECD region have wide varieties of climatic and weather conditions, seasonal differences, still they are combined into one category to study their future energy demand and projected emission. India and China are considered as two separate regions to study their energy demand in detail as both regions continue to flourish from the perspective of economic growth and population, and therefore may lead in global energy consumption and emission in the future. Hence these two regions draw special interest inside TIMES G5 model. The model horizon of the modeling aspect ranges from 1990 to 2100, with 19 periods having unequal time span (5, 8 and 10 years) and six smallest time slices. Discount rate of 5% is applied for cost computation. GDP, population, ton-kilometer and person-kilometer are the drivers of the energy demand inside the model. The GDP and population of these five regions are taken jointly from /IEA 2004/ and /POLES 2001/ till 2050. From 2050 to 2100 is projected by considering the past trend of growth rates. The development of GDP and population for five regions in TIMES G5 model is narrated in chapter 4 of general assumption section. Person- and ton-kilometer demand is taken from SAGE model till 2050 and the past trend of growth rate is considered for projection till 2100 that has been presented in section 4.3 of chapter 4.

Energy demand of each region is considered from different WEO publications of IEA till 2030. Based on those demands, the key indicators are developed and the future growth of the key indicators are calculated on past trend of growth rate. The value of each key indicator is provided inside the key indicator section of chapter 4. The indicator approach has been developed for industry, commerce, residence, transport and non-energy use sectors and for each type of useful energy demand in these sectors. The future value of key indicator is considered by logic in some cases. On the demand-side, it is assumed that the historical shifts from non-commercial to commercial fuels and towards cleaner and flexible, grid-transported energy carriers at the final-energy level increase into the future. Market share for the hydrogen operated transport system and synthetic fuel operated vehicles has been given inside the base case for some regions.

The reserve and resource amount of different region are taken from /SAUNER 2000/, IEA statistics and other studies for the five regions on energy carriers: coal, lignite, crude oil and natural gas. These figures are given in the reserve and resource section 4.5 of chapter 4. The future exploration of the energy carriers is considered by taking account of past pattern of mining and extrapolation growth. The extraction cost and inter-regional transportation cost of energy carriers are taken from /SAUNER 2000/ and /OPEC 2004/. The past investment of the technologies are calculated and taken inside the model from its commissioning and decommissioning curve (Annex A). The refinery capacity for each region is taken from BP statistics and the future refinery situation is open to the model decision.

Minimum share of renewable is considered inside this study for each region from the statistics of /WEO 2004/ and from some regional studies (Annex A). The value of minimum renewable electricity production from different renewable energy carriers is considered for different regions.

The developed and developing regions use the solar boiler and also solar PV for the decentralised electricity production on the rooftop. Solar PV system penetrate marginally inside the energy system, as the governments are taking steps to promote the decentralised electricity production through the subsidy scheme and also the use of more renewable energy to ease the burned on fossil fuel, which directly controls the pollution level from global and local point of view. India has already started this subsidy scheme on solar PV, small hydro and wind turbine /mnes/. The small-scale industries can be benefited from this type of scheme to fulfil their electricity demand with lower cost. China has implemented the subsidy scheme in its energy infrastructure through R&D, IPP, renewable, resource, projects and incentives like lower interest rate on loan and taxation privilege /gov.cn.ziliao/.

The development of the capacity installation for nuclear electricity generation in EU25 rises from 127 GW in 1990 to 145 GW in 2050 and onwards the capacity remains constant as the lower value. Likewise for R_OECD the capacity installation starts from 148 GW in 1990 and increases to 187 GW in year 2050 and afterwards the lower limit of the capacity is kept as 180 GW. For R_NOECD region the capacity installation of nuclear starts from 42 GW in year 1990 and increases to around 300 GW in year 2100 linearly as the lower bound. In the case of India, the installation of new capacity on nuclear technology starts from

2 GW in year 2005 and reaches to 11 GW in year 2100 linearly increase in fashion. China follows the same trend like India for the nuclear power plant installation.

The load factor of the technologies for different energy carriers considered different inside this study as there are different technologies based on each energy carrier, e.g., gas based electricity producing plant, CHP plant, peaking turbine, internal combustion engine, etc. The load factor of each energy carrier based technologies is given below. For nuclear technologies the load factor lie in-between 0.4 to 0.9, for coal technologies 0.4 to 0.8, for gas technologies 0.4 to 0.8, for oil technologies 0.4 to 0.7, for hydro technologies 0.41 to 0.5, for pump storage technology 0.25, for fuel cells 0.6, for fusion technology 0.7, for biomass technology 0.45 to 0.7, for biogas 0.7, for waste technologies 0.3 to 0.78, for solar technologies 0.26, for wind technologies 0.22 to 0.41 and for geothermal technologies 0.3 to 0.7.

The transmission efficiency of electricity and heat is calculated from IEA statistics and taken for the periods 1990, 1995 and 2000 for respective regions. After the period 2005 the transmission efficiency considered is different for different regions than the IEA projections /WEO 2004/. For EU25 region, the transmission efficiency increases linearly from the value around 0.89 in 2000 to 0.94 till 2020 and after that it remains constant till end of the model horizon. The same assumption has been considered for R_OECD but the value of transmission efficiency in the year 2000 is slightly in lower side in year 2000 compared to EU25. The assumption of the periods, for R_NOECD, India and China, to achieve the transmission efficiency of 0.94 is different like 2050, 2040 and 2035 respectively. The transmission efficiency of these regions increases from the value of 2000 to the maximum value linearly and after that it remains the maximum value. As the technology and market share data of this model is not taken from the WEM model. Therefore the result coming from the electricity generation sector is somehow different than the /WEO 2004/ in future years.

In the base case of EU25 the electricity production from oil has been restricted and the share starts from 0.9% upper value in year 2005 and linearly decreases to 0.6% in the period 2100. For R_OECD the value is 5% in year 2005 and decreases linearly to 0.6% in the period 2100. Electricity production from oil in R_NOECD region is taken as 2.5% in year 2005 and 0.5% in year 2100. For India the value has been considered from 5% in year 2005 to 0.2% in year 2100 and for China the values are 5% in year 2005 and 0.11%. The values are provided refers to the upper limit.

Carbon dioxide constraint has not been considered in the base case and also there is no restricition of any type of emission in the base case to understand the energy structure of any region upon its resource carriers and resource to supply energy inexpensively. The learning technologies are handled exogenously inside the base case, i.e., the development of the investment cost with enhancement of time is considered to be decreasing for certain learning technologies and for certain learning technologies the investment cost is constant, e.g., biogasification and geothermal heat pump. The technologies for which the exogenous learning has been considered are integrated gasification combined cycle, combined cycle gas turbine, molten carbonate fuel cell, solid oxide fuel cell, solar PV cell, wind onshore and wind-offshore (see chapter 4.4). For three learning technologies the exogenous new capacity development has been considered from 2005 to 2100 (see Table A-18). They are IGCC, CCGT and geothermal heat pump. The capacity development of wind onshore, wind offshore and solar PV is driven by minimum renewable electricity production by each region.

5.1.2 Global learning scenarios with uncertainty in learning rates

The globa learning scenarios take account of nine technologies to learn globally. It is formulated on minimum, medium and maxmum progress ratios of each learning technology set, i.e, nine technologies formulate three sets of learning scenarios. In the set of minimum progress ratio scenario, each technology of nine technologies included with their minimum progress ratio, aswell the other learning scenarios are formulated like minimum PR. Three learning scenarios are tested on uncertainty on learning rates to know the technology roadmap with uncertainty in learning. To know, how the uncertainty of learning rate affects the technology diffusion. The knowledge gap and time lag concept is not included in these learning scenarios. Floor cost approach of learning technologies are applied to these learning scenarios.

The methodology on floor cost approach as given in chapter 3.2.1.1, has been developed and implemented for learning scenarios to handle the uncertainties on learning rates inside the energy optimization model. The floor cost approach is developed to restrict the drastic and abrupt change of specific cost of the technology subject to uncertainty in learning rates or progress ratios, e.g., the drop of the specific cost reduces even below to the value of 1% of its initial value of the technology, which is not possible. In this case, the model selects the technology to its maximum capacity available in each period. To handle the sudden drop of the specific cost of the technology, floor cost approach has been considered inside this study.

5.1.3 Global learning scenarios subject to knowledge gap and time lag

Three scenarios on global learning have been formulated and tested for three different progress ratios of each technology, with knowledge gap concept presented in terms of higher specific cost, i.e., knowledge gap approach (see chapter 3.2.2.2), in which it is represented that developing regions visualize higher specific cost of the technology than developed regions, though they are using the same product produced in the same year in the manufacturing regions.

In another one approach, two scenarios are formulated on medimum progress ratio, One is for knowledge gap and the other one is for time lag concept, to know difference inbetween the two concepts of technology gap and its effect on the energy system on learning technology diffusion.

5.2 Result analysis

The results of TIMES G5 model presents the past, present and future situation of the global energy system in such a way that it reflects the reliable picture of the energy needs of the regions under given restrictions and scenario assumptions. This research focuses on the future energy system needs from population growth, GDP and transport demand, which type of technology and energy carriers the region integrates inside its energy system such that it is economical and cost effective. The TIMES G5 energy system is modeled by key indicator approach to predict energy demand of the future, for various regions starting from their primary to useful energy demands, anticipate future problems as it pertains to energy needs, and make effective decisions for future energy scarcity and surplus for base case and also for learning scenarios subject to uncertainty in learning rates and different concept on global learning.

5.2.1 Base case

The result analysis of the base case is provided below and the result of the base case is compared with the result of the IEA work /WEO 1995-2004/ to get an overview of the plausibility of the model results.

5.2.1.1 Final energy consumption

Final energy consumption is categorised by the consumption of energy by different end-use sectors. The end-use sectors considered inside this study are the industry, commerce, residence, transport and non-energy use sectors. The summation of the energy demand of the above end-use sectors is reflected as total final energy consumption. The consumption or energy demand by sectors is presented below by regions and also by energy carriers.

- **Transport sector**

The world is going to face the modal shift from region to region in transport sector. Developed regions are tending to switch from individual mode transport to common mode transport to reduce the fuel consumption and environmental emissions. But in case of developing regions, they are continuing to shift from common mode to individual mode due to the unconventional mass transport system, increase in employment rate and high GDP growth. The transport demand of person- and ton-kilometer increases significantly for the developing regions compared to developed regions (see chapter 4.3.2.1). Thus the energy demand increases with higher degree in the developing region than the developed regions.

The total energy demand of world transport sector reaches to 3291 Mtoe in 2030, 4554 Mtoe in 2050, 5609 Mtoe in 2070 and 6952 Mtoe in 2100, as portrayed in Figure 5-2. The transport energy demand increases from 1990 to 2100 by 1.82 times, 2.37 times, 9.85 times, 8.70 times and 18.67 times respectively by EU25, R_OECD, R_NOECD, India and China (see figure Figure 5-1). Out of all, China transport sector has huge improvement on energy demand. Synthetic fuels and bio-fuels enter inside the transport sector of all regions to a small margin, whereas hydrogen is only integrated inside the EU25 and R_OECD regions due to minimum market share. Natural gas and electricity are also the energy carriers of the transport sector of all regions.

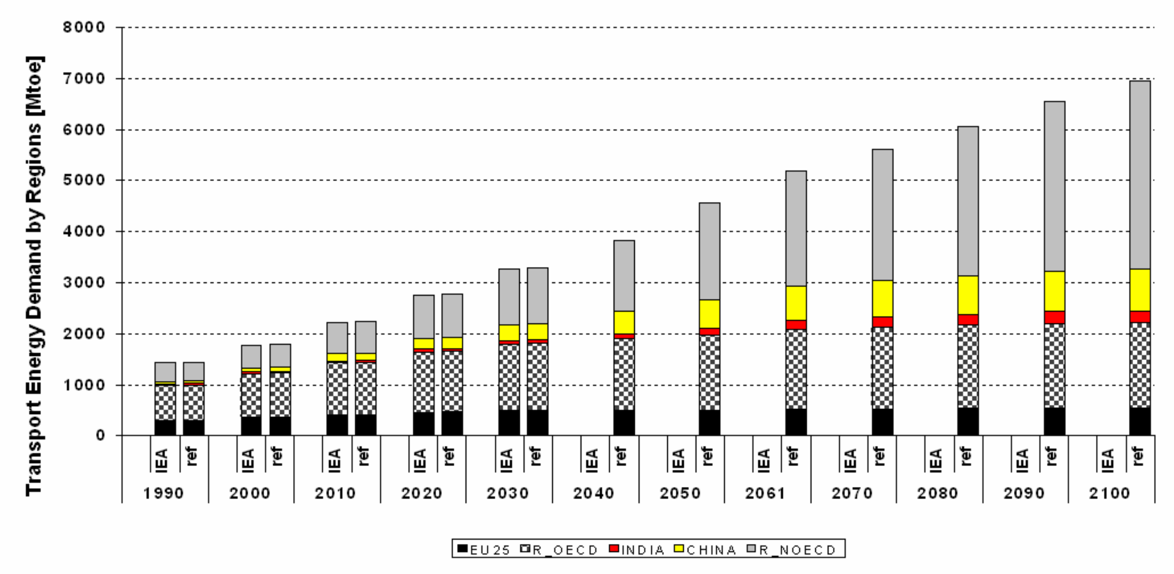

Figure 5-1: Transport sector energy consumption by regions of world

In all time period the share of oil products in the total energy consumption is highest compared to others and maintains a share of more than 90% in all time periods (Figure 5-2). Coal phased out its share gradually from starting to mid period of the model horizon and vanishes thenceforth as the steam locomotive is going to be outdated and inefficient. Also the pollution level of this locomotive is more. Electricity, natural gas, hydrogen, methanol, ethanol and bio-fuels increase their share from staring to end period. The share of hydrogen; synthetic fuel; RME; and methanol and ethanol remain below 0.8%, 1.9%, 2.5% and 0.6% respectively in total energy consumption of transport sector throughout the model periods.

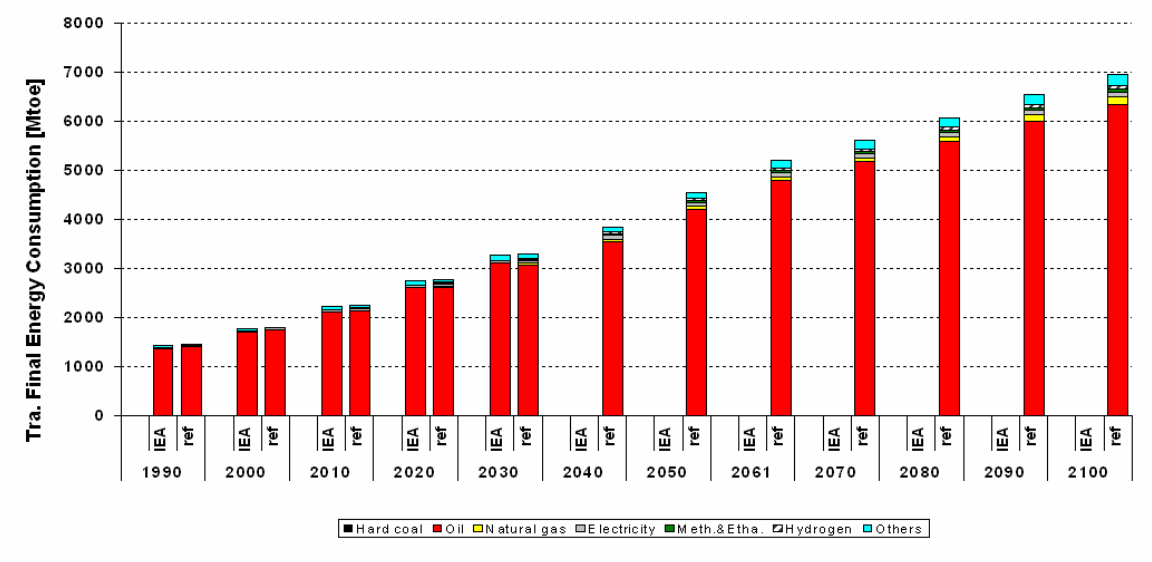

Figure 5-2: Transport sector energy consumption by fuels of world

- **Industry sector**

Industrial energy demand in all regions of TIMES G5 model increases but the increased growth rate for the developed regions are marginal compared to the developing regions (see chapter 4.3.2.2). The developing regions switched to saturated condition from unsaturated condition of industrial energy use and they mingle different type of industries (heavy, medium and light) with respect to their growth of GDP. Thus towards the later phase of the model horizon the industrial energy demand is predominated by developing regions compared to the developed regions. Also shifting of industry type is a major cause for the increase in energy demand. The total demand of world industrial energy arrives at 3389 Mtoe, 4304 Mtoe, 5049 Mtoe and 5636 Mtoe in the years 2030, 2050, 2070 and 2100 respectively as provided in Figure 5-3. Among all regions the R_NOECD has more demand of industrial energy towards the end periods. The rise of the final to initial period of the industrial energy is highest for China, succeeded by India, R_NOECD, R_OECD and EU25. The demand of industrial energy in the year 2100 by EU25, R_OECD, R_NOECD, India and China are 516 Mtoe, 1525 Mtoe, 2406 Mtoe, 363 Mtoe and 825 Mtoe respectively that is depicted in Figure 5-3. The average growth rate of industry sector energy consumption from 1990 to 2100 is 1.04%/a for whole world, whereas 0.38%/a for EU25, 0.79%/a for R_OECD, 1.27%/a for R_NOECD, 1.51%/a for India and 1.55%/a for China.

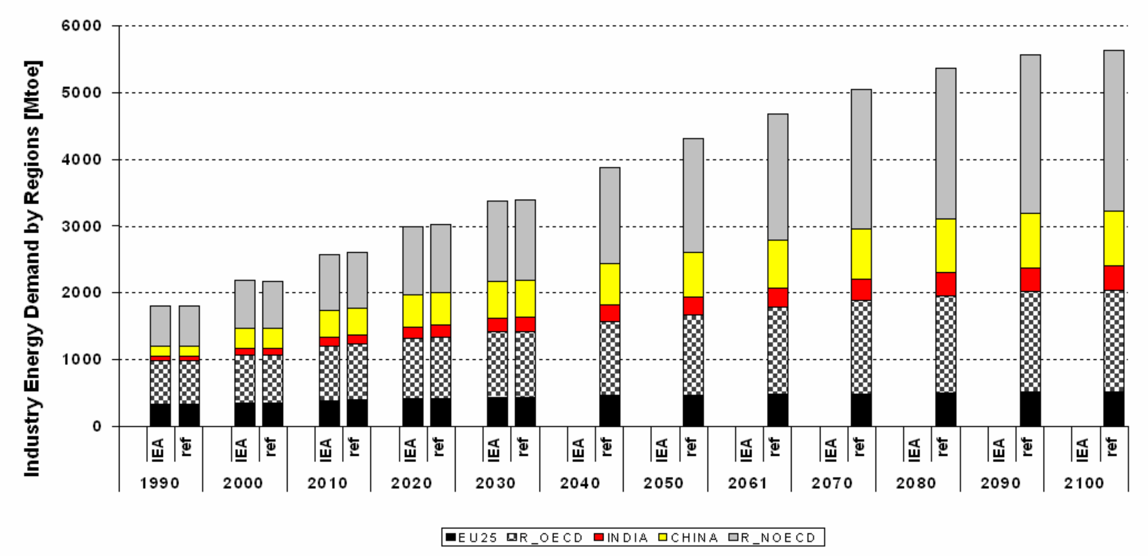

Figure 5-3: Industry sector energy consumption by regions of world

Gas and electricity are main fuels for the industry sector of EU25; while gas, electricity and renewable are the main fuel of the R_OECD region. Coal, electricity, natural gas, oil and renewable are the main constituent of the energy carrier in industry sector of developing regions. The growth of natural gas, electricity and renewables are higher compared to other fuels. Use of natural gas is not high for industrial use in India and China compared to R_NOECD region. As the R_NOECD region has more gas resource and reserves, thus the natural gas enters to a plausible margin in industrial final energy consumption. More or less, all regions integrate natural gas in their energy demand (Figure 5-4), not only minimizing pollution in local and global level, but also generating energy in an efficient manner. The co-firing of the biomass in industry sector increases the industrial energy demand of biomass. Boiler based on waste and hydrogen is introduced inside modelling of this sector but the technology of hydrogen is more costly and is not selected in the base case of any regions. District heating is also used for the fulfilment of the energy demand in this sector. The technology is utilised to some degree for the production of the useful energy demand.

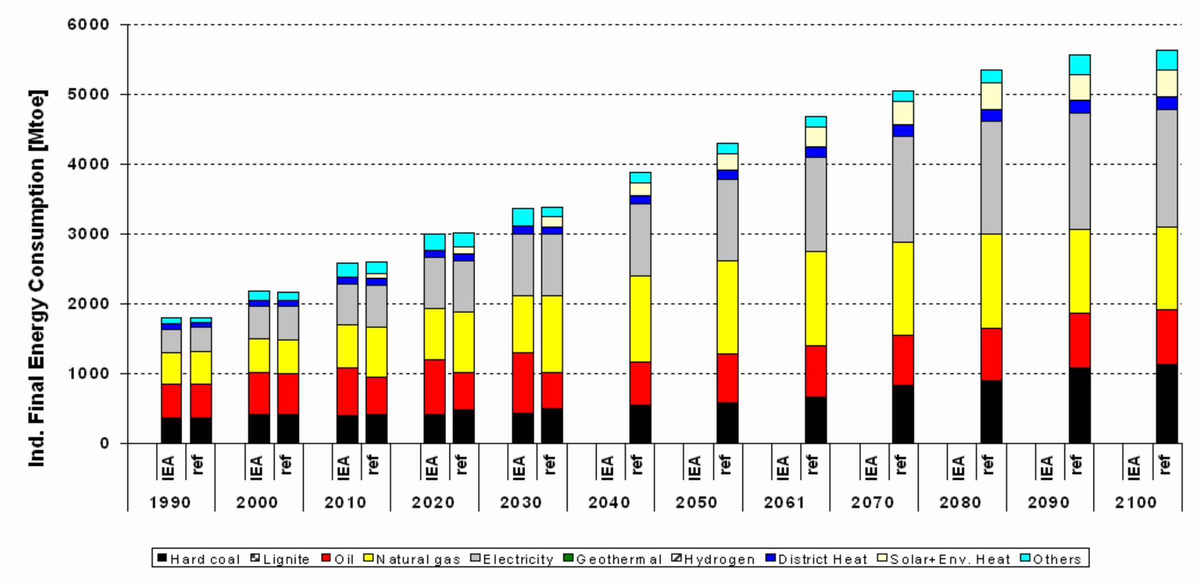

Figure 5-4: Industry sector energy consumption by fuels of world

- **Commerce sector**

The developed regions are already full blown in their commercial energy consumption in this sector, as they are the matured users of commercial machineries and almost at the point of impregnated. Commerce sector is a main driver of energy demand in future for developing regions. The electrical appliances, machinery equipments, lighting devices and other commercial related machinery, those are not introduced in the commerce sector of the developing regions, is introduced in later part of the model horizon. For the increase in commerce sector useful energy demand by developing regions can be referred from the development of the key indicators for commerce sector provided in section 4.3.2.3 of Chapter 4. Therefore the energy demand in the commerce sector jump to higher magnitude in future compared to present situation (Figure 5-5). The commercial energy demand of world reaches to 1658 Mtoe, 2273 Mtoe, 2826 Mtoe and 3183 Mtoe in the years 2030, 2050, 2070 and 2100 respectively. The energy demand in 2100 increases almost 4.04 times compared to its 1990 value. The average growth rate of commerce sector energy consumption from 1990 to 2100 is 1.28%/a of whole world, whereas 0.70%/a for EU25, 0.93%/a for R_OECD, 1.38%/a for R_NOECD, 2.52%/a for India and 2.42%/a for China.

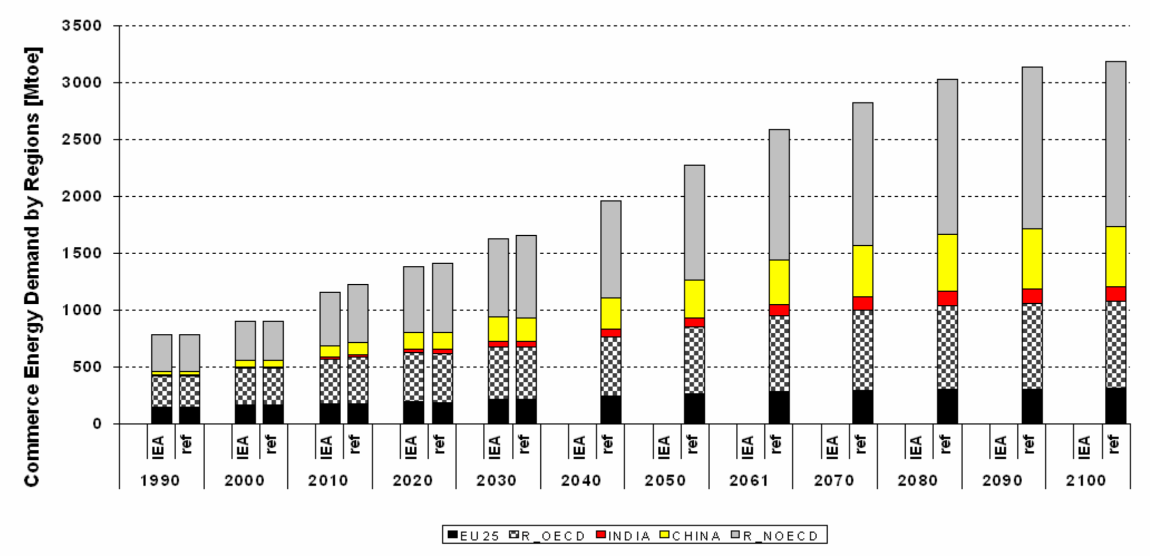

Figure 5-5: Commerce sector energy consumption by regions of world

Commerce sector of all most all regions integrates the increase in value of the energy carriers like solar, district heat, electricity, biomass and natural gas from starting to end periods (see Figure 5-6). But oil looses the market share from starting to end period. Coal decreases the market share towards future compared to today in EU25 and R_NOECD regions, but maintains marginal increase in value for R_OECD, India and China. The major changes occur in the structure of energy consumption, switching of traditional fuel to the commercial fuels, introduction of energy carriers like solar and geothermal. The increase in solar+env.heat arises for the increase in cooling demand across the regions and heat pumps are modeled to fulfil the cooling energy demand. The share of environmental heat is high in heat pumps for which the value is coming high.

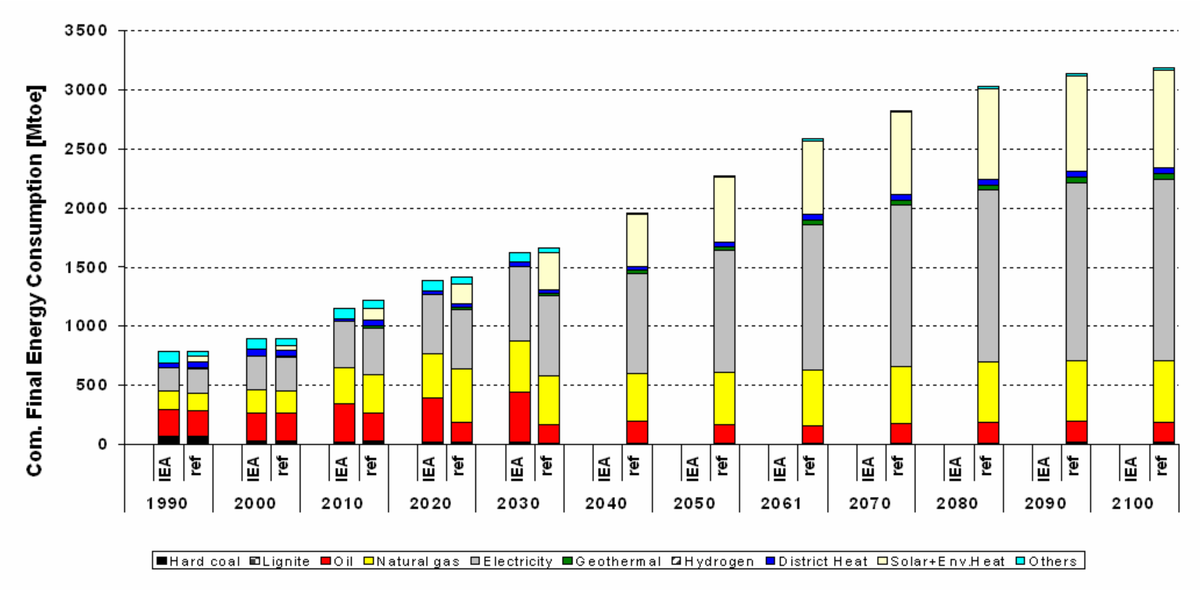

Figure 5-6: Commerce sector energy consumption by fuels of world

- **Residence sector**

The world goes through the reformation phase in the residence sector for energy consumption and appliances utilisation. The energy demand in the household sector of world reaches to 2605 Mtoe in 2030, 3400 Mtoe in 2050, 3808 Mtoe in 2070 and 4081 Mtoe in 2100. The ratio of the residential sector energy use of world varies 2.68 times, in-between the initial and final periods of the model horizon (see section 4.3.2.4 of chapter 4). The average growth rate from 1990 to 2100 of residential energy consumption is 0.9%/a on world basis.

In EU25 household sector, the energy consumption remains more or less stable throughout the model horizon (Figure 5-7). Though the household energy demand in EU25 increases to some extent for the utilisation of new appliances but the population figure follows the continuous declining trend in which both factors try to neutralise each other. Natural gas, electricity, district heat and solar+env.heat energy consumption in household sector increase from starting to end period and other energy carriers decline their values substantially or remain stable. Household energy consumption in R_OECD region increases 1.76 times from beginning to end period. Natural gas, solar+env.heat, electricity and district heat increase their share and other polluting fuels find the route of phase-out by passage of time (Figure 5-8). Energy demand of residential sector in the region R_NOECD increases around 4.52 times from starting to end period. Almost all energy carriers in this region increase their value with progress of time. Biogas and solar+env.heat energy enter to a significant margin. Biogas is used in cooking purpose and solar+env.heat energy is used for the cooking, heating and cooling purpose. The household energy consumption increases around 2.92 times for India from starting to end period of the model. Almost all energy carriers increase their shares from starting to end period except biomass. In case of China, the energy consumption increases 2.1 times from beginning to end period. Polluting fuels decrease from starting to end period but non-polluting fuels increase their share in this region. Natural gas, solar+env.heat, biogas, electricity and geothermal energy increase in total energy mix.

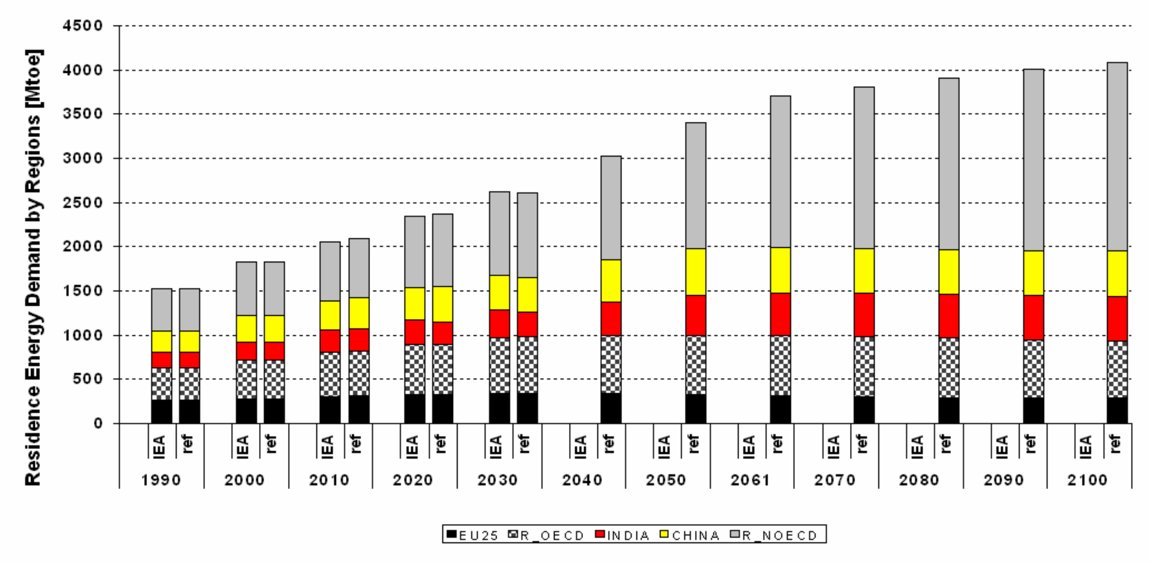

Figure 5-7: Residence sector energy consumption by regions of world

Electricity, solar, natural gas and geothermal energy enter marginally from starting to end period, whereas the conventional fuels and heavy emitting fuels loose the market share as shown in Figure 5-8. Solar technologies for cooking increases its market share and penetrate potentially as the entire regions has enough solar potential that is free and a better source of renewable. Solar boiler for heating purpose is modeled and does not penetrate significantly as the cost of investment is too high. The emitting fuels, e.g., coal, natural gas and oil loose to small extent their market shares in year 2100 compared to 1990. Biomass reduces substantially its share from 1990 to 2100 especially in developing regions. The penetration of biomass in household sector of India and China is considered to reduce from 72% in year 2000 to 8% in year 2100 for cooking purpose provided by upper limit. Similarly for heating purpose, it reduces from 67% in year 2000 to 9% in year 2100 given by upper limit. The phase out of the biomass is considered on the ground of indoor pollution of toxic smoke, suspended particulates and local environmental pollutions. These pollutions cause categorically the diseases of bronchitis, respiratory disorder, respiratory illness, asthma and Chronic Obstructive Pulmonary Diseases (COPD) that is the cause of high percentage premature mortality rate in China and India. The share of biomass in total final energy consumption in residence sector of world decreases from around 37% in year 1990 to around 10% in the year 2100.

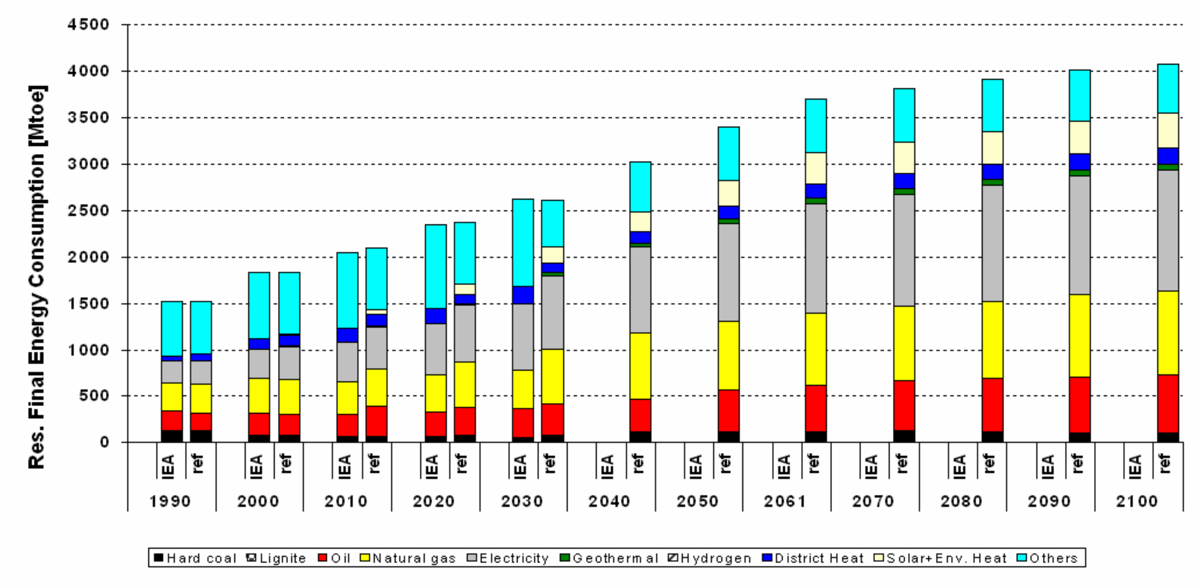

Figure 5-8: Residence sector energy consumption by fuels of world

- **Non-energy use sector**

Non-energy use of white spirit, paraffin, waxes, lubricants, bitumen and other products are coming from oil products; natural gas; carbon blacks and graphite electrodes are coming from coal. Non-energy use of these products is exclusively non-energy use and not accounted inside the sector-wise energy consumption /OECD 1999/.

The world attains the value of non-energy use of 328 Mote in 2030, 424 Mtoe in 2050, 495 Mtoe in 2070 and 545 Mtoe in 2100 compared to 232 Mtoe in 1990 (see Figure 5-9). It is almost 2.35 times, i.e., the growth rate of 0.78%/a from starting to end period. The non-energy use of EU25 region amplifies 1.54 times in the year 2100 (52 Mtoe) compared to the value of the year 1990 (34 Mtoe). In case of R_OECD region the non-energy use increase 2.25 times from 1990 (63 Mtoe) to 2100 (141 Mtoe). The ratio of final period to initial period non-energy use for R_NOECD, India and China respectively are 1.78 times, 5.08 and 5.21 times. Non-energy use increases to a greater degree for India and China for more use of non-energy products (e.g., lubricants, spirit, paraffin, waxes, graphites, etc.) as the population, person- and ton-kilometer demand increase.

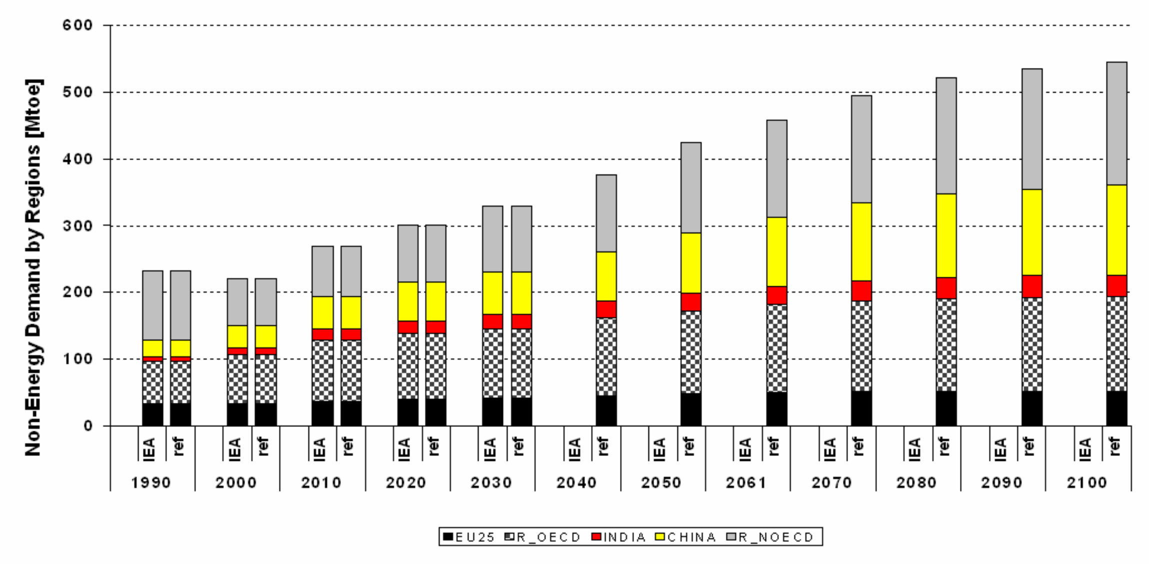

Figure 5-9: Non-energy use sector energy consumption by regions of world

- **Total final energy consumption**

The total final energy consumption sums all sectoral energy demand (e.g., transport, industry, commerce, residence, non-energy use, etc.) of world reaches to 8425 Mtoe in 2010, 11272 Mtoe in 2030, 14955 Mtoe in 2050, 17787 Mtoe in 2070 and 20396 Mtoe in 2100 as given in Figure 5-10. The rise of total energy consumption in the year 2100 compared to 1990 is approximately 3.52 times, which is comparable to the MESSAGE model of IIASA (see section 2.4.8 of chapter 2). The growth of the energy demand per year is peaked from 2030 to 2050 due to the high GDP and population growth of the developing regions. After the period 2050, the saturation on the energy demand reaches in these regions. The developed regions do not show increase of the final energy demand aggressively like developing regions (Figure 5-10) as the energy consumption in all sectors is in saturation level and also the population decreases as time proceeds for EU25, while in the case of R_OECD the population more or less remains stable (see Table 4-1). It was R_OECD region that prevailed all regions, on energy consumption point, during the initial period of the model horizon. But the region R_NOECD takes place the position of the region R_OECD towards the end periods. The percentage increase of total final energy consumption for China and India compared to their end and initial period is too high, as these two regions are passing through high GDP and population growth.

According to the energy carriers (Figure 5-12), oil takes the highest share inside the total final energy consumption. The second and third position is occupied by the electricity and natural gas. The world is going towards fuel of cleaner, easily assessable, transportable and easily convertible from one form to another. Share of oil in year 2100 in total final energy consumption is around 41.24%, coal around 6.35%, electricity around 22.6% and natural gas around 13.67% and other energy carriers fills the rest of the shares. In total final energy consumption, coal has small portion of shares, which comes from India and China in their end use sectors. Electricity more or less enters in all sectors of all regions. Oil is the fuel for transport sector of all regions but it enters heavily inside the developing regions for the high growth rate of person- and ton-kilometre demand. Natural gas has significant share in all sectoral energy demand of all regions. It enters in large quantity in the industry and residence sector of developed regions and R_NOECD, whereas, for cooking in residence sector of India and China.

All sectors realize increase in energy demand from starting to end period (see Figure 5-11). Transport sector is the leading energy consumer towards the end period and descending order is maintained by industry, residence, commerce and non-energy use. The increment in energy demand by the transport sector occurs for the heavy demand of person- and ton-kilometer and also the switching of the transport mode, i.e., mass mode to individual mode in the developing regions. The increase in demand in industry sector arises for the increase in appliances. Commerce and residence sector energy consumption increases as the appliances penetrate highly in both the sectors of developing regions.

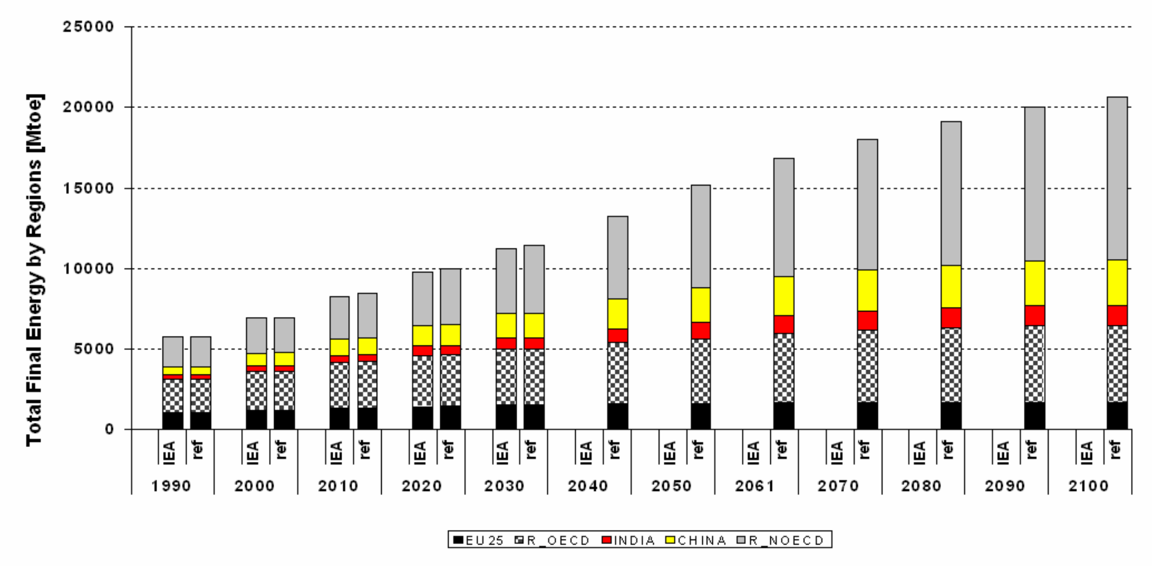

Figure 5-10: Total final energy consumption by regions of world

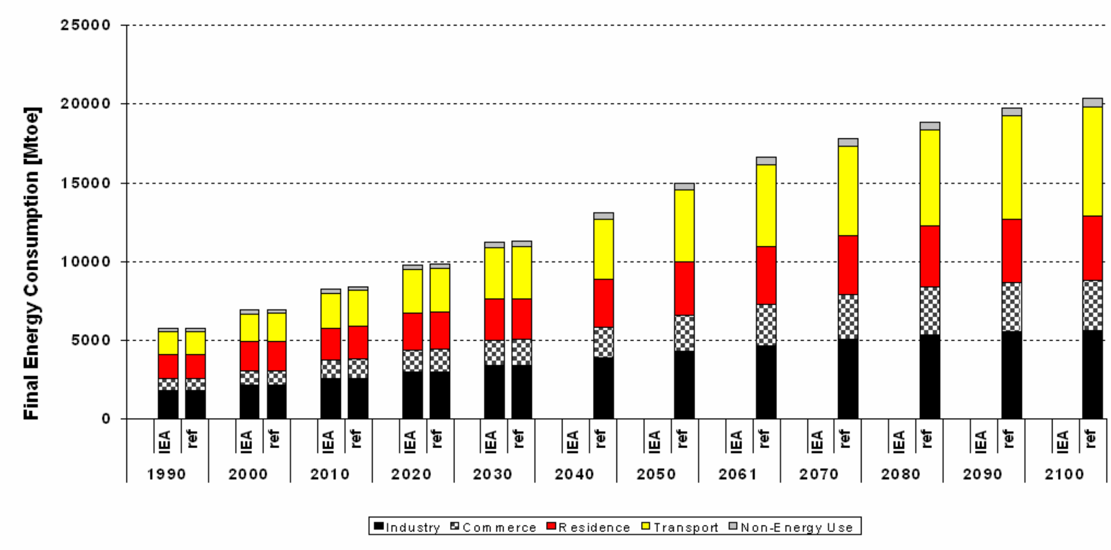

Figure 5-11: Total final energy consumption by sector of world

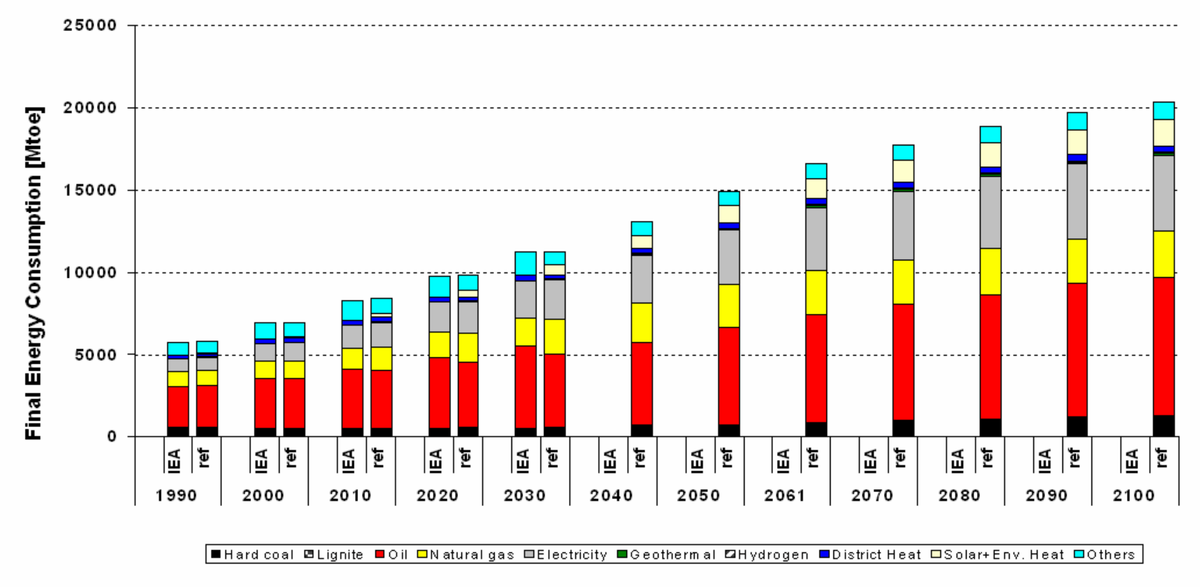

Figure 5-12: Total final energy consumption by fuels of world

The average growth rate of total final energy consumption from 1990 to 2100 is 1.15%/a for whole world, whereas 0.41%/a for EU25, 0.77%/a for R_OECD, 1.54%/a for R_NOECD, 1.36%/a for India and 1.58%/a for China. Total final energy consumption per GDP of whole world decreases from 0.169 ktoe/€(00) in year 1990 to 0.064 ktoe/€(00) in year 2100 with average growth rate of –0.879%/a. This implies the growth of GDP is higher compared to growth of energy demand and increases in energy efficiency. Likewise the total final energy consumption per capita of world increases from 1.128 toe/capita in year 1990 to 2.008 toe/capita in year 2100 with average growth rate of 0.525%/a, reflecting the increase in energy demand per capita.

5.2.1.2 Power generation sector

Power and heat production is the main sector inside each regional model of TIMES G5. This sector produces electricity and district heat for other sectors. The power production unit is modeled with technologies of electricity producing plants, Combined Heat and Power (CHP) plants and boilers (see section 4.4.2 of chapter 4 and Annex A). After production, energy is transported to other sectors for utilization. Electricity is categorized by high, medium and low voltage to be supplied for utilization in other sectors.

- **Electricity demand and production**

The electricity demand by industry, commerce, residence and transport sector increases from the starting to end period as shown in Figure 5-13. The maximum growth of electricity demand from period 2010 to 2050 is around 1.7%/a; from 2030 to 2050 is 1.4%/a; and later period the overall growth per annum deceases. It is due to the shifting of the heavy industries to light industry and high penetration of electrical appliances or gadgets inside the residence and commerce sector. Transport sector demands certain amount of the electricity due to the penetration of electricity operated rails and cars. The most influential sector in future electricity growth is household and commerce sectors.

The major changes happen in the structure of residence and commerce sectors electricity use especially in developing regions (see Figure 5-14). Out of all regions India, China and R_NOECD region explores their electricity demand.

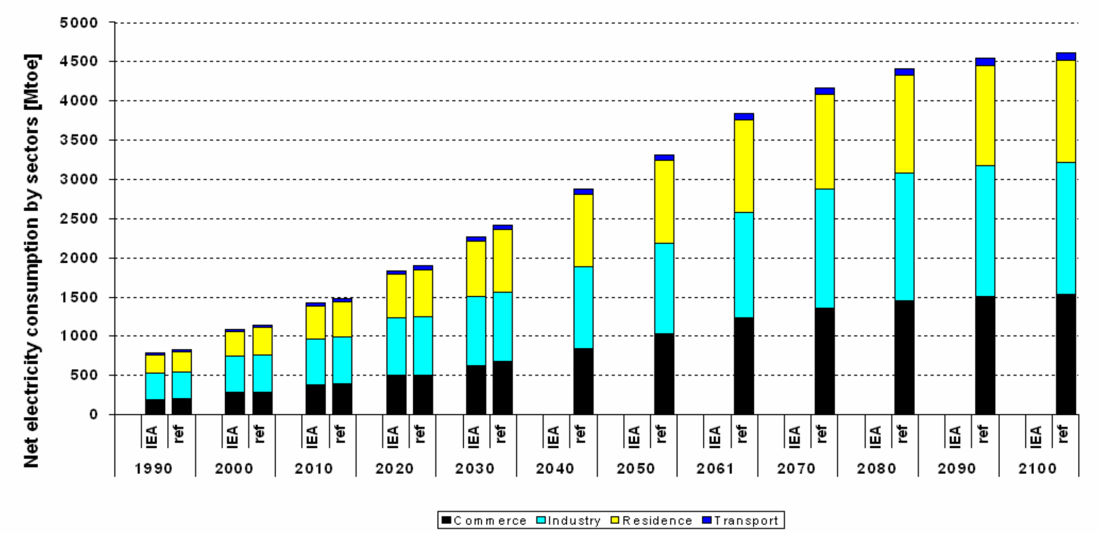

Figure 5-13: Electricity demand by sectors of world

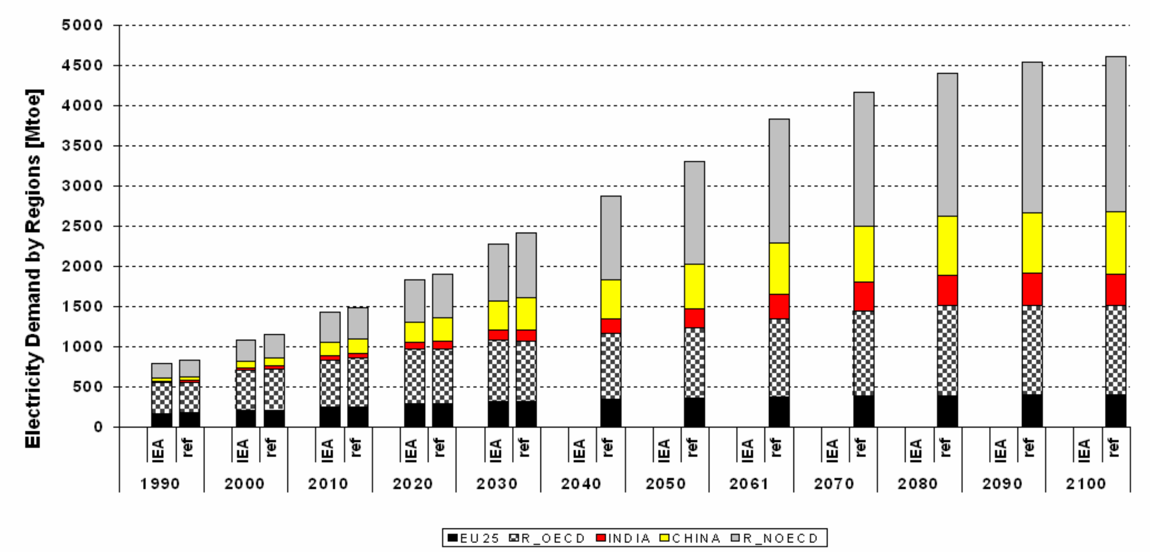

Figure 5-14: Electricity demand by regions of world

The average per capita electricity consumption by world increase from 575 kWh/capita in the year 1990 to 1339 kWh/capita in the year 2050 and to 1492 kWh/capita in the year 2100. In case of developed regions, the per capita electricity consumption is higher in the initial and final periods as compared to the developing regions. The minimum value of per capita electricity demand (717 kWh/capita) is observed for India and maximum (4037 kWh/capita) for R_OECD region.

The gross electricity generation of world increases rapidly and reaches 20543 TWh in 2010, 31214 TWh in 2030, 41021 TWh in 2050, 51551 TWh in 2070 and 57101 TWh in 2100, as provided in Figure 5-15. In electricity production hard coal, hydro, nuclear, natural gas and oil shares in descending order in the initial period of the model horizon. But towards the end period of the model horizon, the share of natural gas increases as the electricity production increases from natural gas in R_OECD and R_NOECD regions those have high natural gas resource and maintains the share around 44.9%. Likewise the share of the hard coal is around 27.5%, hydro 11.7%, nuclear 10.3%, wind 1.7% and rest are by other renewable, lignite and oil. The other renewable consist of biomass, biogas, waste, geothermal and solar. Oil has very small value of share in electricity generation towards the end periods. The maximum and minimum share of renewable in total electricity generation comes within the range of one to five percent for world in different periods. The share of renewable increases from starting to end period as all regions tries to integrate to certain percentage of renewable electricity in their energy mix. The developed regions go for more percentage and the developing regions to lesser percentage because of the high cost of renewable electricity. The renewable share of EU25 and R_OECD regions varies from minimum 2% to maximum 18%. In case of developing regions R_NOECD, India and China, the share of renewable in total electricity generation varies in between 1% to 7% from starting to end period. The share comes from the minimum limit of the renewable electricity production from renewable given inside the model.

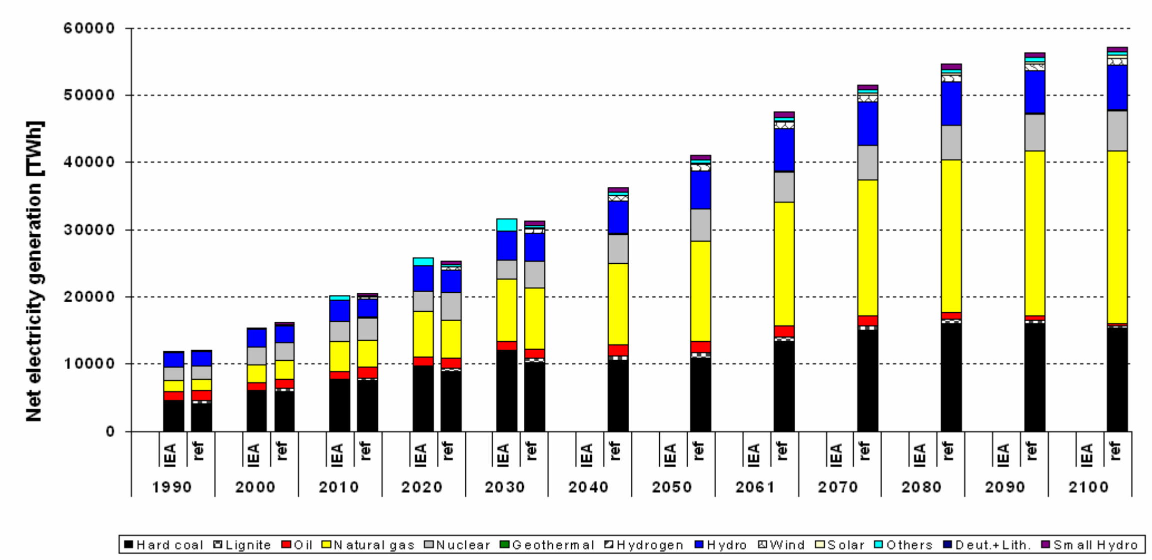

Figure 5-15: Net electricity generation by fuels of world

India and China depends heavily on coal, nuclear, natural gas and hydro mainly for their electricity production in future, whereas R_OECD and EU25 mainly depends on the natural gas, hydro, wind, nuclear and renewable. The production of nuclear electricity in EU25 and R_OECD increases till the period 2040 and decreases thenceforth towards the end period /WEO 2004/. Natural gas, hydro, nuclear and coal are important energy carriers for the production of electricity in the region R_NOECD. The electricity generation by regions and also by fuels are different from 2005 onwards inside the model compared to the work of IEA because of the differences in efficiency figures considered inside the model than IEA and also the lower limit given for renewable electricity. The total electricity generation till 2030 by this model differs from the value of /WEO 2004/ due to different in assumption of the transmission efficicency and transport loss in regional models than the IEAs /WEO 2004/ assumption (see chapter 5.1.1).

- **Capacity development**

The capacity of electricity producing plants increase from the starting to end period of the model horizon and reaches to 9778 GW in 2100 compared to 2827 GW in the year 1990. The capacity reaches 5821 GW in 2030, 7543 GW in 2050 and 9060 GW in 2070. The value of the total capacity by regions and by energy carriers is given in the Figure 5-16 and Figure 5-17. The capacity of natural gas is highest in the year 2100 and the descending order is followed by coal, hydro, nuclear, wind and solar. The capacity increases 3.46 times from starting to end period with an average growth rate of 1.13%/a; and also the overall utilization rate increases approximately from 0.5 in year 1990 to 0.54 in year 2010, 0.61 in year 2030, 0.63 in year 2055 and 0.66 in year 2100.

The overall high utilization factor of the system for electricity production originates from the high load factor of the technologies considered for the energy carriers like coal, oil, gas and nuclear (see chapter 5.1.1) and also the integration of low value of minimum renewable electricity those have high load factor. The time resoulution of the load curve has significant effect on the overall utilization rate of the electricity production sector and in this study, it is considered as six segments. The peak flux and also the peak reserve margin decrease towards the end period of the model horizon, those have significant effect on the increase in overall utilization rate towards the end period of the model horizon. Also the technology switching restriction is not imposed inside the model for which the overall utilization factor increases. The efficiency of the transmission is considered in higher side compared to the /WEO 2004/ work. Therefore the electricity production reduces in future years (after 2005) and the capacity development also. Developed regions and R_NOECD integrates more gas-based plants for electricity production. In case of India and China, they integrate more coal plants, as the coal is abundant and cheap energy carrier having high reserve and resource in these regions. Electricity capacity based on hydro increases in China, India and R_NOECD regions.

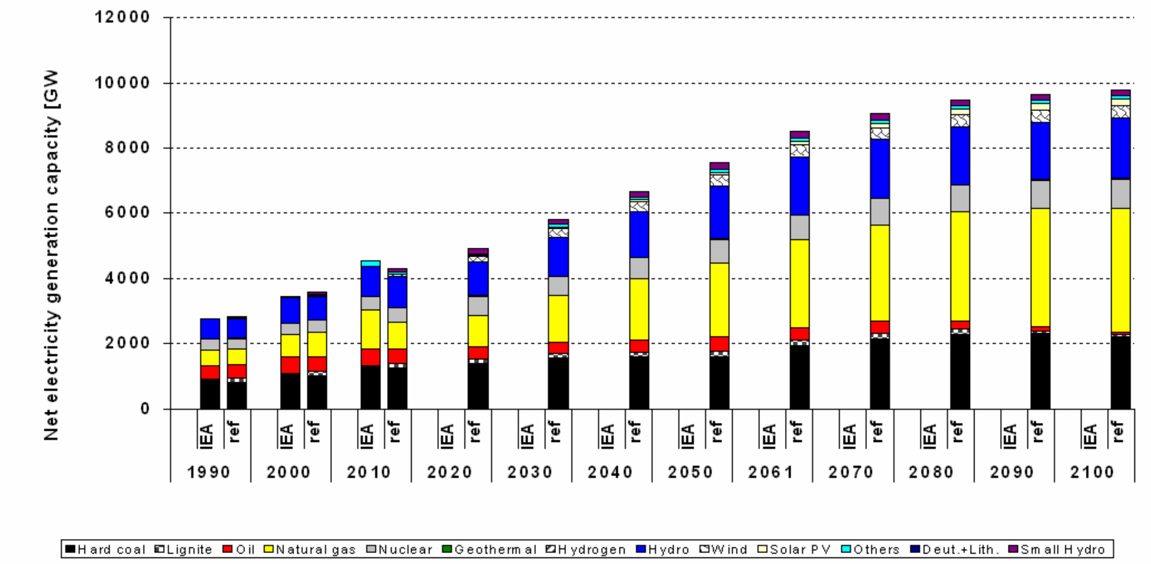

Figure 5-16: Net electricity generation capacity by fuels of world

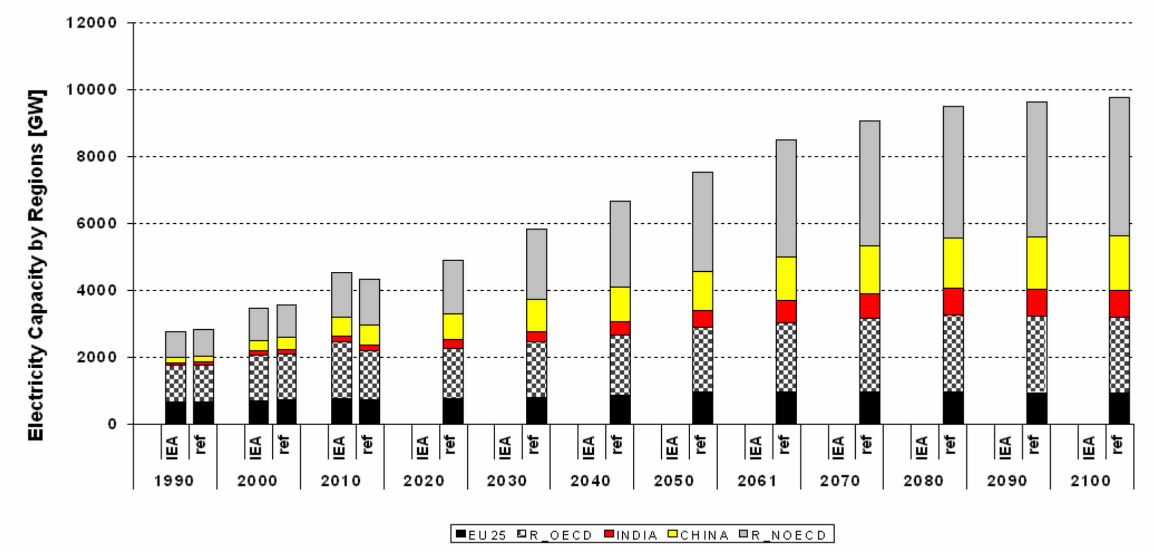

Figure 5-17: Net electricity generation capacity by regions of world

Integrated gasification combined cycle and combined cycle gas turbine predominate in electricity and heat production sector than other technologies. Solar PV, wind onshore and wind offshore enters in the base case to satisfy the user constraints of minimum renewable electricity production from these energy carriers. Biomass, biogas, waste and geothermal based technologies penetrate marginally to fulfil the minimum electricity production from these energy carriers. Although some technologies are modeled inside this study but they do not enter in the base case. Such technologies are fusion, fuel cells and bio-gasification technolgoies. Exogenous learning is considered for some learning technologies inside this model, e.g., combined cycle gas turbine, integrated gasification combined cycle, wind onshore, wind offshore, solar PV, molten carbonate fuel cell and solid oxide fuel cell also for some non-learning technologies, exogenous learning has been considered. The technology development of some technologies are coming by introduction of minimum development of the new capacity, e.g., IGCC, CCGT and geothermal HP and for some others, it comes from the minimum renewable electricity production, e.g., solar PV, wind onshore and wind offshore. The technologies of biofasification, solid oxide fuel cell and molten carbonate fuel cell neither subjected to minimum new capacity development nor minimum electricity production. Both minimum new capacity development share and minimum electricity production has influence on the penetraton of the technologies. The development of the cumulative capacity for the learning technologies (see section 3.2.1.2 of chapter 3) for whole world is provided in the Table 5-1. The implicit learning rates and progress ratio has been calculated for the learning technologies those are considered as exogenous learning in the base case. The learning rate of IGCC is 0.01, CCGT is 0.006, solar PV is 0.05, wind onshore is 0.02 and wind offshore is 0.01. The progress ratios of the exogenous learning technologies are on higher side compared to the progress ratios considered inside the learning scenarios analysis (see Table 3-2).

Table 5-1: Cumulative capacity of the learning technologies in the base case [GW]

Technology	1990	1995	2000	2010	2025	2040	2061	2100	Implicit learning rates
	[GW]								[fra.]
Biogasification	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Integrated gasification CC	0.00	0.00	0.00	0.80	124.60	702.30	2649.00	5029.50	0.01
Combined cycle GT	0.00	0.00	0.00	29.80	449.60	1503.60	2462.30	4916.20	0.006
Molten carbonate fuel cell	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00
Solid oxide fuel cell	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solar PV	0.10	0.30	0.60	5.90	36.80	84.90	183.50	339.40	0.05
Wind onshore	1.70	4.30	17.70	74.00	211.20	366.40	552.60	672.50	0.02
Wind offshore	0.00	0.00	0.20	9.50	62.50	140.80	262.30	432.30	0.01
Geothermal HP	0.00	0.00	0.00	11.20	53.80	117.50	213.90	334.70	0.00

5.2.1.3 Primary energy consumption

The primary energy demand of whole world reaches to 15169 Mtoe in 2030, 19451 Mtoe in 2050, 23257 Mtoe in 2070 and 26579 Mtoe in 2100 as depicted in Figure 5-18. The share of primary energy by EU25 varies from 18.2% in 1990 to 8.7% in year 2100; likewise the share of R_OECD varies from 36.3% in 1990 to 23.1% in 2100. In case of R_NOECD, it varies from 32.3% in 1990 to 46.5% in 2100, for India it is 4.4% in 1990 and 6.8% in 2100, for China the value is 8.7% in 1990 and 14.9% in 2100. Thus it is concluded that the regions EU25, R_OECD, R_NOECD and China changes their share in total, to a greater extent than India. Developing regions gain share, whereas developed regions loose their shares. The main reason is that the developing regions are under unsaturated condition of the energy use at present and the increase in economic growth and standard of life drags these regions for more primary energy demand in the future. The primary energy demand of world increases 3.29 times from starting to end period of the model horizon. The work of /Morita et al./ claims the primary energy demand variation within 1990 to 2100 will lie in-between 2.3 times to 6.7 times. Also, B2 scenario of MESSAGE world model by IIASA speculates primary energy consumption in year 2100 as 3.86 times higher than the year 1990 (see section 2.4.8 of chapter 2).

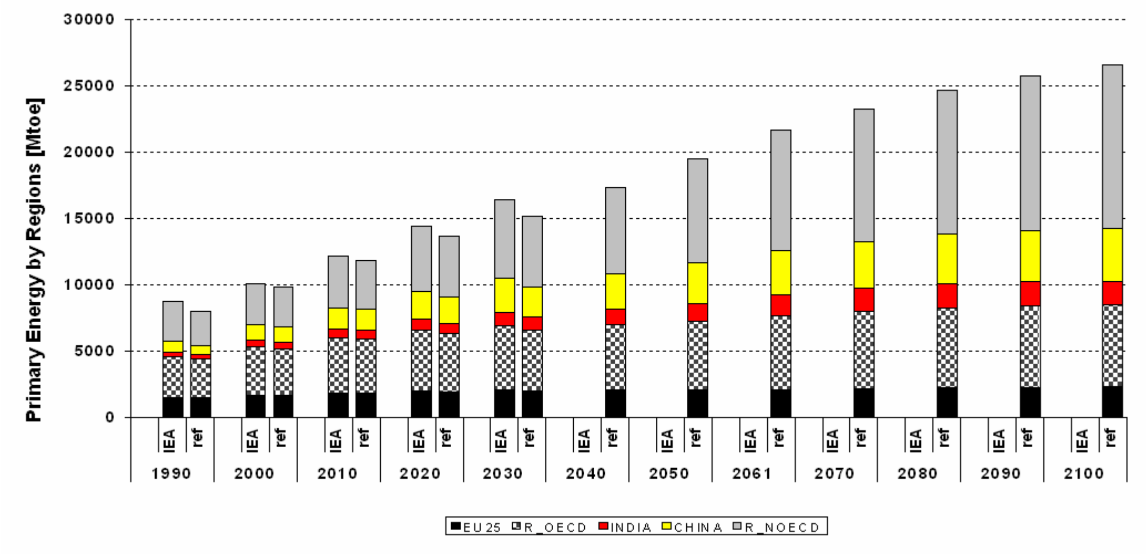

Figure 5-18: Primary energy consumption by regions of world

In total primary energy consumption, oil holds a biggest share throughout the model horizon as shown in Figure 5-19. Coal remains as second while gas has the third position towards the initial time period of the model horizon but towards the end period gas supersedes coal and replaces it. Oil and coal slightly lose their market shares from 1990 to 2100, i.e., from 38.2% and 23.8% to 33.7% and 17.3% respectively. Natural gas gains its market share from the starting period to end period (17.4% in 1990 to 27.9% in 2100).

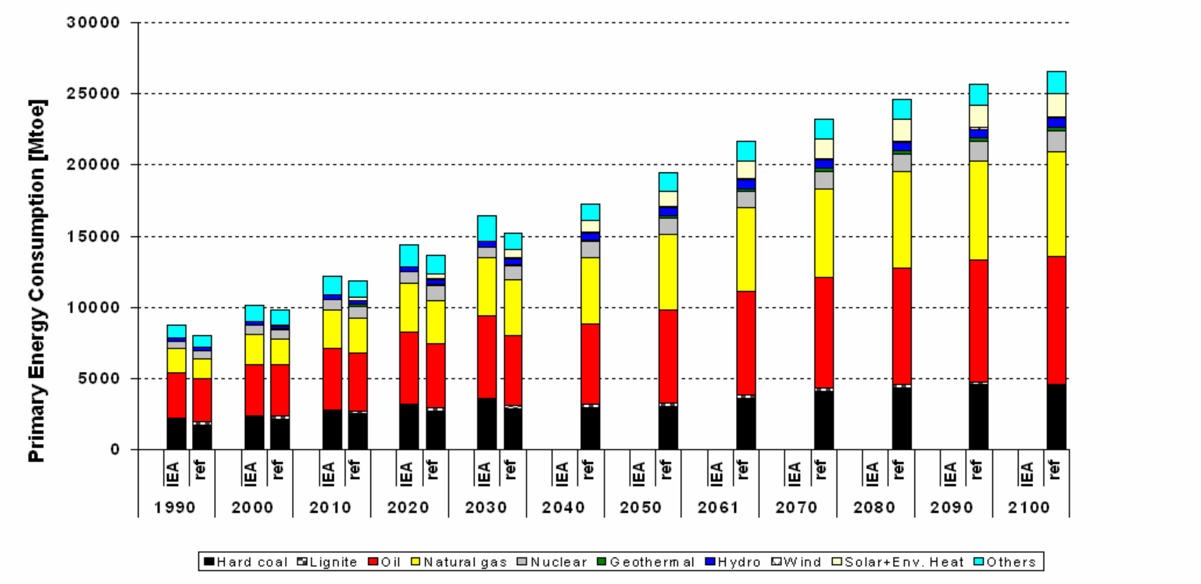

Figure 5-19: Primary energy consumption by fuels of world

Nuclear and hydro maintain certain share in the primary energy consumption; hydro is used for the electricity production only and nuclear for electricity and heat production. Geothermal energy is used in the heating; electricity production and cooling purpose and enters to a marginal degree inside the energy system. Solar energy penetrates marginally inside the energy system as the regions use solar cooker for cooking, solar boiler for heating and boiling water.

In primary energy consumption EU25 region integrates more natural gas followed by oil and coal as this region use more gas in all end use sectors and also the electricity and heat production sector, whereas R_OECD region integrates more oil followed by natural gas and coal. Transport demand is the important driver of heavy oil demand in all regions. R_OECD uses more gas compared to other energy carriers. The region R_NOECD consumes more natural gas followed by hydro and coal. More natural gas is selected inside this region as the region has enough gas resource and reserve. India consumes more coal in its primary energy consumption, and further position is occupied by oil and biomass as coal is the main energy for electricity sector and oil is more consumed in future heavy growth of transportation. The decreasing order of energy carriers in China's primary energy consumption is coal, oil, uranium, biomass and hydro. Coal is used more in the electricity production sector and also in industry sector. Oil increases for the high growth of transport demand and uranium is used more in the electricity production sector to fulfil the exponential growth of electricity demand.

The average growth rate of total primary energy consumption from 1990 to 2100 is 1.1%/a for whole world, whereas 0.4%/a for EU25, 0.7%/a for R_OECD, 1.4%/a for R_NOECD, 1.5%/a for India and 1.6%/a for China. Primary energy consumption per GDP (energy intensity) of world decreases from 233 toe/€(00) in year 1990 to 83 toe/€(00) in year 2100 with average growth rate of –0.93%/a. This implies the growth of GDP is higher compared to growth of energy demand. Likewise the primary energy consumption per capita increases from 1.6 toe/capita in year 1990 to 2.6 toe/capita in year 2100 with average growth rate of 0.44%/a, reflecting the energy demand increase per capita. Some indicator based on GDP and population has been developed during this work and provided in the Table 5-2.

Table 5-2: GDP and population related indicators

Region	Indicator	Unit	1990	2030	2061	2100	Growth rate [%/a]
							1990-2100
EU25	Primary energy/GDP	[toe/k€(00)]	0.2020	0.1203	0.0979	0.0972	-0.66
	Final energy/GDP	[toe/k€(00)]	0.1493	0.0937	0.0769	0.0713	-0.67
	Ton-kilometer/GDP	[TKM/€(00)]	0.2433	0.2264	0.2168	0.2027	-0.17
	Primary energy/capita	[toe/capita]	3.3992	4.4613	5.5263	6.9123	0.65
	Final energy/capita	[toe/capita]	2.5121	3.4756	4.3365	5.0729	0.64
	Person-kilometer/capita	[kPKM/Capita]	10.5878	16.8417	21.5332	24.7167	0.77
R_OECD	Primary energy/GDP	[toe/k€(00)]	0.2481	0.1535	0.1282	0.1190	-0.67
	Final energy/GDP	[toe/k€(00)]	0.1749	0.1158	0.1000	0.0921	-0.58
	Ton-kilometer/GDP	[TKM/€(00)]	0.3872	0.3376	0.3222	0.2971	-0.24
	Primary energy/capita	[toe/capita]	4.7546	5.4757	6.2242	7.2615	0.39
	Final energy/capita	[toe/capita]	3.3518	4.1331	4.8580	5.6240	0.47
	Person-kilometer/capita	[kPKM/Capita]	17.9163	20.6120	24.7233	28.0208	0.41
R_NOECD	Primary energy/GDP	[toe/k€(00)]	0.2551	0.1813	0.1379	0.1179	-0.70
	Final energy/GDP	[toe/k€(00)]	0.1838	0.1380	0.1084	0.0939	-0.61
	Ton-kilometer/GDP	[TKM/€(00)]	0.3849	0.2982	0.2522	0.2121	-0.54
	Primary energy/capita	[toe/capita]	1.2277	1.3242	1.7692	2.1485	0.51
	Final energy/capita	[toe/capita]	0.8848	1.0080	1.3908	1.7117	0.60
	Person-kilometer/capita	[kPKM/Capita]	3.6687	3.9428	5.5502	7.6844	0.67
INDIA	Primary energy/GDP	[toe/k€(00)]	0.2363	0.1022	0.0692	0.0523	-1.36
	Final energy/GDP	[toe/k€(00)]	0.1887	0.0720	0.0486	0.0363	-1.49
	Ton-kilometer/GDP	[TKM/€(00)]	0.2673	0.2360	0.2145	0.1662	-0.43
	Primary energy/capita	[toe/capita]	0.4199	0.6533	0.9253	1.0520	0.84
	Final energy/capita	[toe/capita]	0.3355	0.4601	0.6494	0.7306	0.71
	Person-kilometer/capita	[kPKM/Capita]	1.5735	2.9451	4.9386	5.7376	1.18
CHINA	Primary energy/GDP	[toe/k€(00)]	0.3949	0.1093	0.0747	0.0602	-1.70
	Final energy/GDP	[toe/k€(00)]	0.2845	0.0724	0.0534	0.0432	-1.70
	Ton-kilometer/GDP	[TKM/€(00)]	0.5506	0.2741	0.2448	0.1838	-0.99
	Primary energy/capita	[toe/capita]	0.6139	1.5880	2.3662	2.7051	1.36
	Final energy/capita	[toe/capita]	0.4422	1.0514	1.6938	1.9425	1.35
	Person-kilometer/capita	[kPKM/Capita]	1.7128	5.1499	11.0706	12.4142	1.82

- **Cumulative supply cost data by regions**

The supply cost data of each region is depicted in the Table 5-3 for four different energy carriers of hard coal, lignite, crude oil and natural gas in four steps. P_COIL1 presents the crude oil of step 1 in supply cost curve and P_COIL4 presents the crude oil of step 4. Likewise P_HCO stands for hard coal, P_LIG stands for lignite and P_NGAS stand for natural gas. The extraction of each energy carrier in each step is presented by the cumulative amount, i.e., the years included inside the model horizon from 1990 to 2100. The marginal cost of each step energy carrier production is presented in the Table 5-3. The marginal cost of production of any energy carrier of any region in any step is always greater than or equal to the supply cost curve given in the chapter 4.5. The difference of the shadow price arises for the import of same energy carrier from other regions, which is in higher side compared to extraction cost as it bears the transport cost of the energy carrier and also sometimes the hotelling rule comes to play that increases the shadow price of energy carriers.

Table 5-3: Supply cost data by regions

Cumulative production [EJ] and the corresponding cost [€(00)/GJ]										
Energy Carrier	EU25		R_OECD		R_NOECD		INDIA		CHINA	
	[EJ]	[€/GJ]	[EJ]	[€/GJ]	[EJ]	[€/GJ]	[EJ]	[€/GJ]	[EJ]	[€/GJ]
P_COIL1	13.6950	0.7976	371.5195	0.4097	6768.3747	0.2454	34.4910	0.6463	109.1300	0.6430
P_COIL2	70.4800	1.0740	4339.6745	0.4182	8092.2822	0.4182	25.7515	0.8820	123.0870	0.9470
P_COIL3	131.5462	1.2309	1488.3037	0.8487	7184.4554	0.8487	13.6555	1.1082	91.1465	1.1199
P_COIL4	12.5772	2.0081	0.0000	0.0000	1659.2802	1.8081	0.0000	0.0000	16.0640	1.3590
P_HCO1	442.0769	0.2460	1979.8884	0.2460	1504.5051	0.2460	1424.8812	0.2460	1946.3823	0.2460
P_HCO2	309.4409	0.5535	1385.9103	0.5535	1579.7314	0.5535	468.1540	0.5535	1351.6445	0.5535
P_HCO3	132.5988	0.6642	593.9371	0.6642	677.0086	0.6642	142.4553	0.6642	2108.5873	0.6642
P_HCO4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
P_LIG1	134.6677	0.1363	210.5775	0.1587	277.9511	0.2460	17.6796	0.2460	31.0537	0.2460
P_LIG2	44.1981	0.3075	126.9896	0.3075	119.0965	0.5535	7.8384	0.5535	26.5132	0.5535
P_LIG3	0.0000	0.0000	85.7543	0.5535	0.0000	0.0000	7.1803	0.6642	18.1651	0.6642
P_LIG4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
P_NGAS1	450.3151	0.6225	1141.2189	0.3567	3376.6919	0.3567	9.5930	1.9461	241.5763	0.7611
P_NGAS2	775.8253	1.2669	1825.9691	1.2669	906.6181	1.2669	44.3017	2.2325	203.5842	1.5308
P_NGAS3	713.4144	2.0786	1597.7222	2.0786	7948.4112	2.0786	79.5795	3.5642	120.5319	2.2173
P_NGAS4	0.0000	0.0000	0.0000	0.0000	3786.7713	2.9765	67.9404	5.5082	1.4680	2.2721

5.2.1.4 CO_2 emission

Global warming and increase of atmospheric temperature is believed for the increase in GHGs emission concentration in the atmosphere in the base case. The concentration of the CO_2 increases progressively as the demand of energy and fossil fuel consumption increases. The world CO_2 emission reached 23931 Mt in 2000, 35450 Mt in 2030, 45283 Mt in 2050, 53930 Mt in 2070 and 61103 Mt in 2100 (see Figure 5-21). The emission figure inside this global model, i.e., from 1990 to 2100 refers approximately to the value of 590-ppmv (1265 GtC in the atmosphere) atmospheric CO_2 stabilisation on the assumption of total CO_2 emission goes to the atmosphere. The rapid growth zone of energy demand and CO_2 emission is from 2020 to 2060. The growth rate of CO_2 from 2000 to 2100 is 0.94%/a; and from 2020 to 2060 is 1.15%/a. In the first half of the century the CO_2 emission increases to a higher degree and in the later half of the century, it reduces for more use of natural gas in R_NOECD, EU25 and R_OECD, nuclear energy in EU25, R_OECD, R_NOECD, India and China, hydro energy in India, China and R_NOECD. Also renewable penetrates to certain margin of the total electricity production due to execution of minimum renewable share in each regional electricity sector.

Different regions contribute different percentage of emission from the starting to end period of the model horizon. R_OECD region contributes maximum share (37.9%) in total CO_2 emission in the year 1990 and other regions EU25, R_NOECD, India and China shares respectively 20.6%, 30.0%, 2.9% and 8.6% could be visualised from Figure 5-20. In the end period of the model horizon, R_NOECD holds the largest share and top position. The share of CO_2 in total, by different regions, in year 2100, is 8.0%, 23.9%, 45.6%, 7.2% and 15.4% by EU25, R_OECD, R_NOECD, India and China respectively.

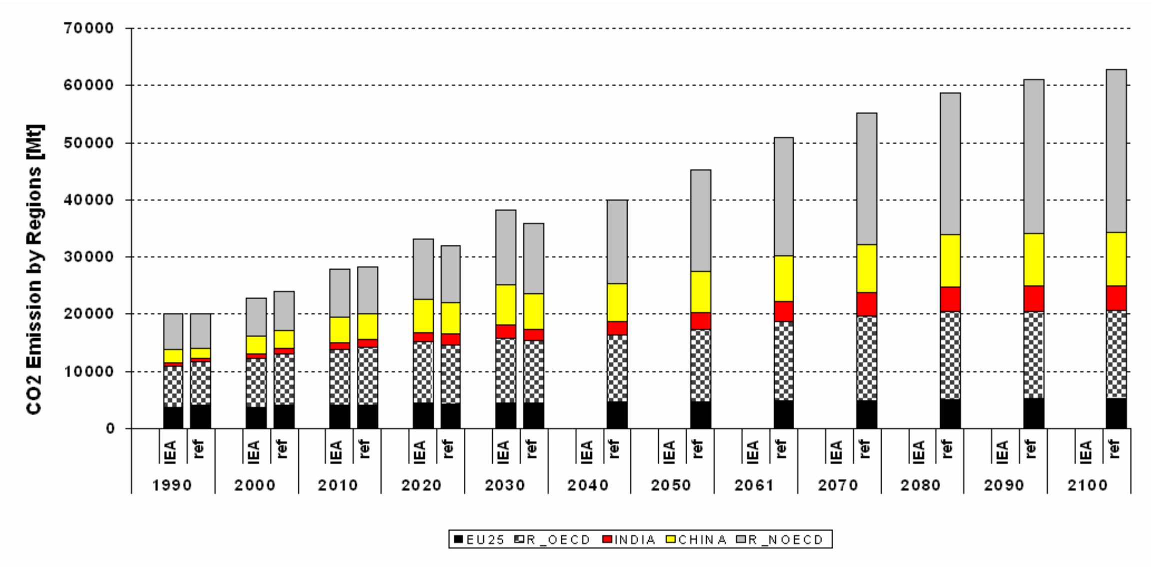

Figure 5-20: Total CO_2 emission by regions of world

The emission by oil products is highest in all periods among all other energy carriers. The next position is taken by coal and natural gas as portrayed in Figure 5-21. Though the use of natural gas increases towards the end period of the model horizon, still it is the least emitter as natural gas emits less CO_2 per unit of energy consumption. The shares of the emissions by coal, natural gas and oil products change from 1990 to 2100 respectively by 37.4% to 29.1%, 16.3% to 28.4% and 47.8% to 46.0% respectively.

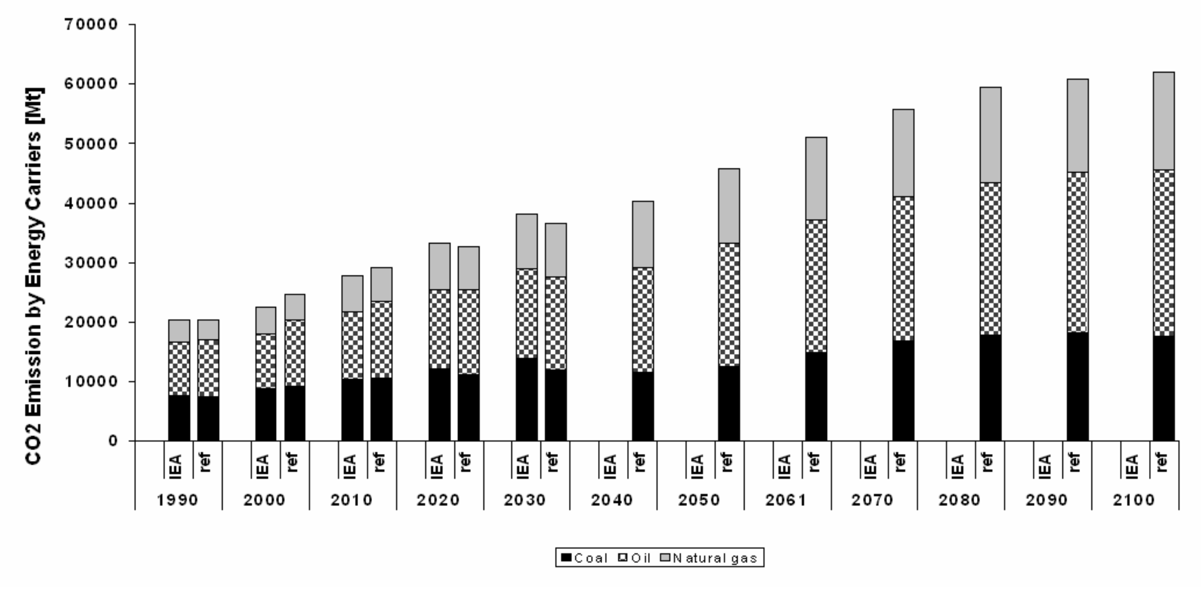

Figure 5-21: Total CO_2 emission by fuels of world

Among different sectors, power generation sector emits more carbon dioxide in all periods of the model horizon. Transport sector follows the power sector and posed to second largest emitter of carbon dioxide. In period 1990 carbon dioxide emission by power generation; refinery and synthetic fuel production; industry; commerce and residence; transport and non-energy use sectors are respectively 35.4%, 2.4%, 20.0%, 16.8%, 21.5% and 3.7% that has been shown in Figure 5-22. In the year 2100 by the same sequence of sectors respectively share 35.9%, 2.9%, 15.9%, 9.8%, 32.6% and 2.9%. Power sector switches from high emitting fuels to low emitting fuels and integrates more nuclear, whereas transport sector increases its share in total emission. Refinery and synthetic fuel production marginally increases its market share, whereas the industry, non-energy use, commerce and residence sector looses their share in total CO_2 emission.

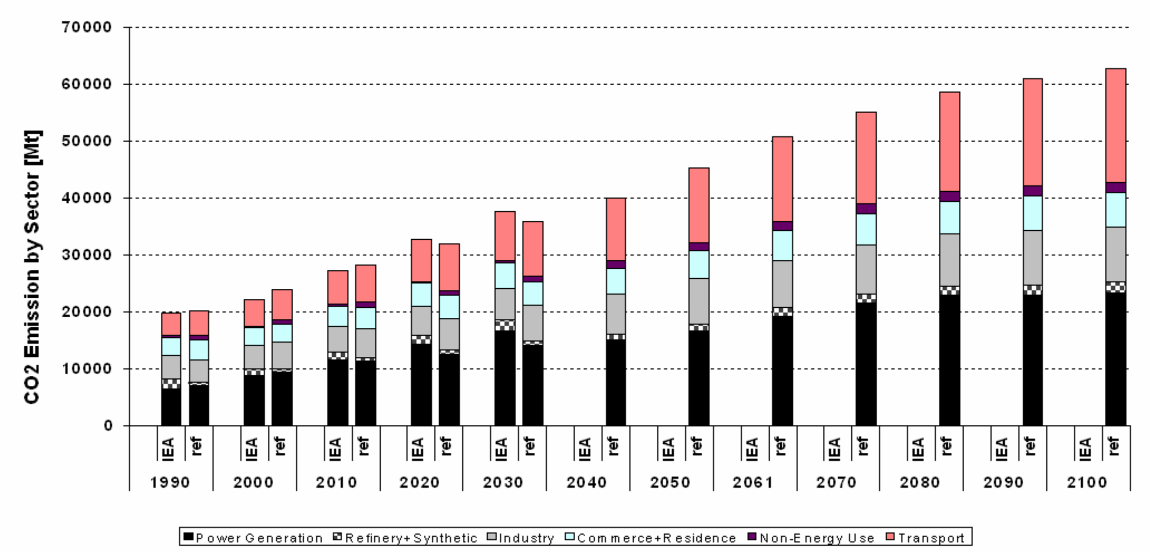

Figure 5-22: Total CO_2 emission by sectors of world

The carbon dioxide emission per primary energy is calculated as the total carbon dioxide emission per total primary energy use. This indicator says about the status on integration of high and low emitting fossil fuels, nuclear and renewable fuels. In this work the value of carbon dioxide per primary energy decreases around 8.4% from period 1990 (2.51 ton/toe) to 2100 (2.3 ton/toe) of the model horizon. The carbon dioxide per total final energy consumption decreases from the value of 3.48 ton/toe in period 1990 to 2.99 ton/toe in period 2100. This indicates that the end use sectors consume more non-emitting or less emitting carbon fuels.

The indicator developed on carbon dioxide to GDP decreases with respect to time that reflects that the growth of GDP is higher than the growth of carbon emission and also it pronounces, about the share of less or non-emitting fuels integration. The value of carbon dioxide per GDP reduces around 3.1 times between its two end periods, i.e., in-between 1990 (0.586 ton/k€(00)) and 2100 (0.191 ton/k€(00)). The carbon dioxide emission per capita of world increase as the energy consumption takes incline in trend. This figure for world starts from 3.92 ton/capita in 1990 and reaches to 6.02 ton/capita in 2100. The increase in carbon dioxide per capita implies the increase in fossil fuel use and high emitting fuels.

5.2.1.5 Climate stabilization of 550 and 500-ppmv

The climate stabilization of 550-ppmv and 500-ppmv stabilization cases has been conducted inside this work to know the influence of the climate stabilisation test on sectoral energy production, consumption, change in energy structure, temperature rise of atmosphere and deep ocean layer. TIMES is suitable to conduct the climat estabilisation cases as it has been integrated the climate module with climate equations adopted from /Nordhaus and Boyer 1999/. The climate equations used linear recursive equations for the calculation of concentrations and temperature changes. By giving the CO_2 concentration of the upper atmosphere for different ppmv, the test of climate stabilization could be conducted.

Energy consumption in transport sector decreases in these scenarios test. Total transport energy demands decreases in the climate stabilization tests compared to the base case and also the share of the energy carriers change in total energy mix. The energy consumption pattern changes from 2010 onwards inside the transport sector for 550-ppmv stabilization and 500-ppmv stabilization cases. Coal and oil consumption decrease in the transport sector in each time period. Less CO_2 emitting fuels like bio-diesel, natural gas, electricity, methanol, ethanol and hydrogen increase in the transport sector energy demand. Each region in TIMES G5 model changes their energy consumption structure by fuel carriers in transport sector.

Industry sector energy consumption decreases in the case of climate stabilization cases. High polluting and low efficient technologies like coal and oil reduced their share in final energy consumption. The share of efficient, low emitting and non-emitting fuels increases in the consumption, e.g., natural gas, electricity, hydrogen and renewables like biomass, solar, etc. Fuel cell enters inside the climate stabilization case towards the end periods. In industry sector, the initiation of the fuel switching takes place from 2005 onwards. The reduction of the total industrial energy demand decreases around 1% of the base case. Total industrial energy consumption decreases in all regions.

Commerce sector keeps the total energy consumption nearly constant in different periods compared to the base case with exception of fuel stwitching from high emitting to low emitting. The reduction of the fossil fuel takes place (e.g., coal, oil, etc.), low emitting fuels and renewable share increases (e.g., electricity, natural gas, district heat and renewable). In all regions, total energy consumption in the commerce sector remains nearly the same by periods with respect to the base case.

Total residential energy consumption decreases by periods compared to the base case in climate stabilization cases. The reduction of residential energy consumption is observed in all regions. The reduction of total energy consumption compared to base case remains about 5%. Coal, oil and natural gas reduce their share in different periods, whereas the shares of electricity, geothermal, solar, biomass, biogas and district heat increase. The structure of energy consumption by energy carriers change in all regions and also the total energy consumption in the residence sector. There is no change in the structure of the energy consumption in non-energy use sector. Total final energy consumption decreases in climate stabilization case compared to the base case by total, by regions and by sectors with less influence on commerce sector. The decrease of total energy consumption remains within 4% in the climate stabilization cases. The change in structural energy demand of transport, residence, industry and total final energy consumption is shown in the Figure 5-23, Figure 5-24, Figure 5-25 and Figure 5-26 to get an overview on change in energy structure of end use sector on climate stabilization cases.

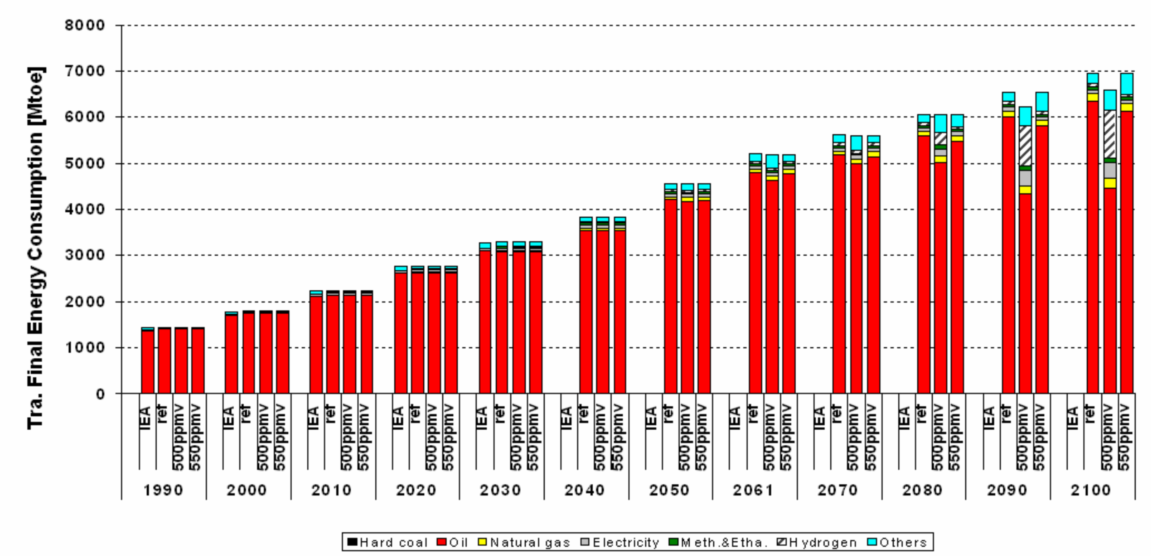

Figure 5-23: Change in structural energy demand of transport sector

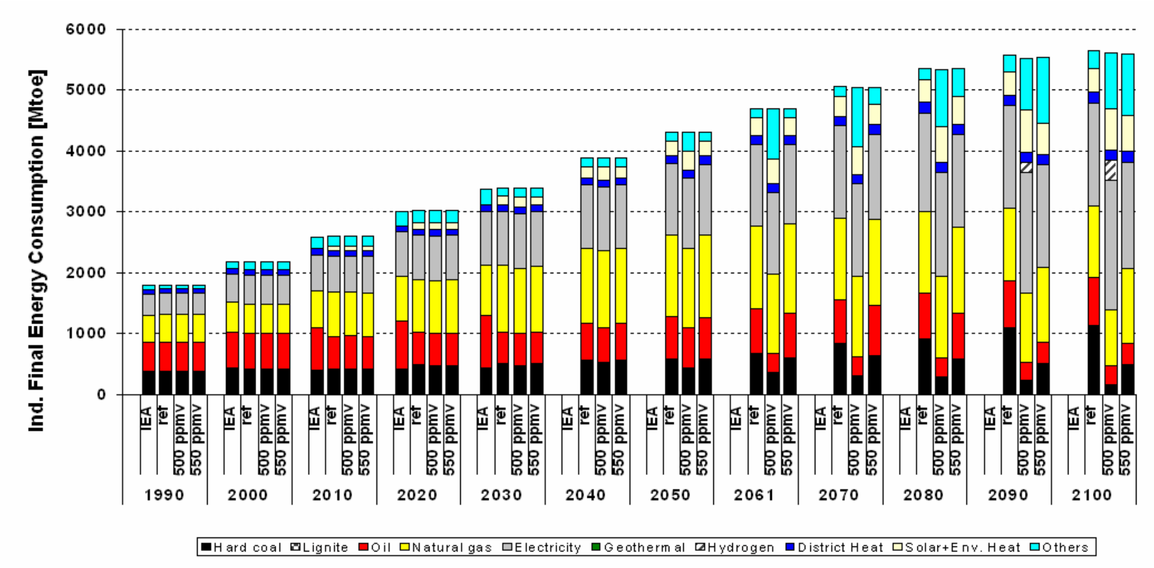

Figure 5-24: Change in structural energy demand of industry sector

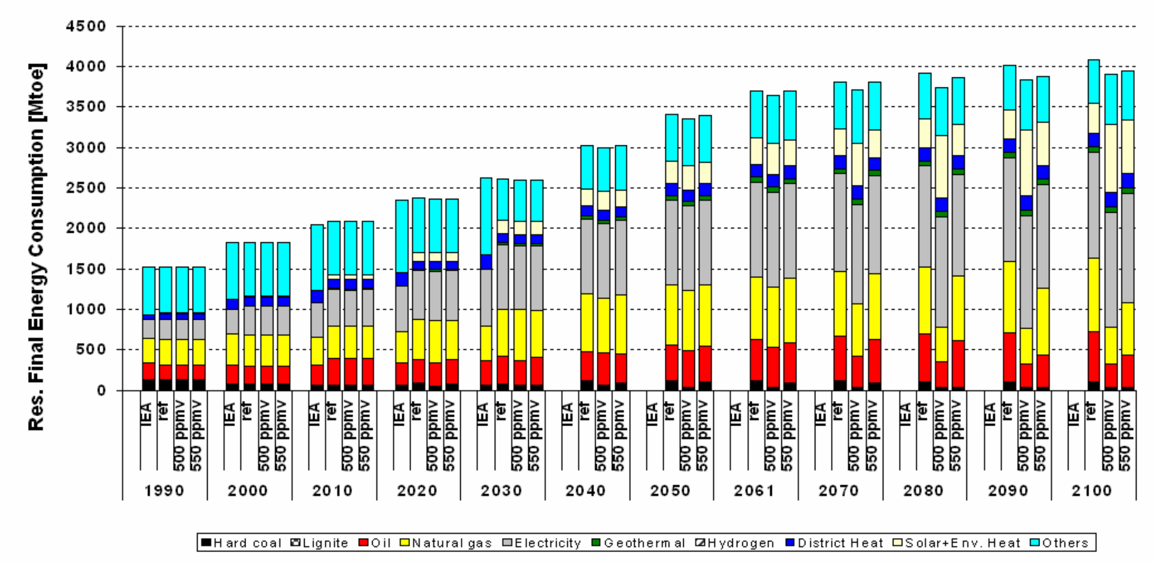

Figure 5-25: Change in structural energy demand of residence sector

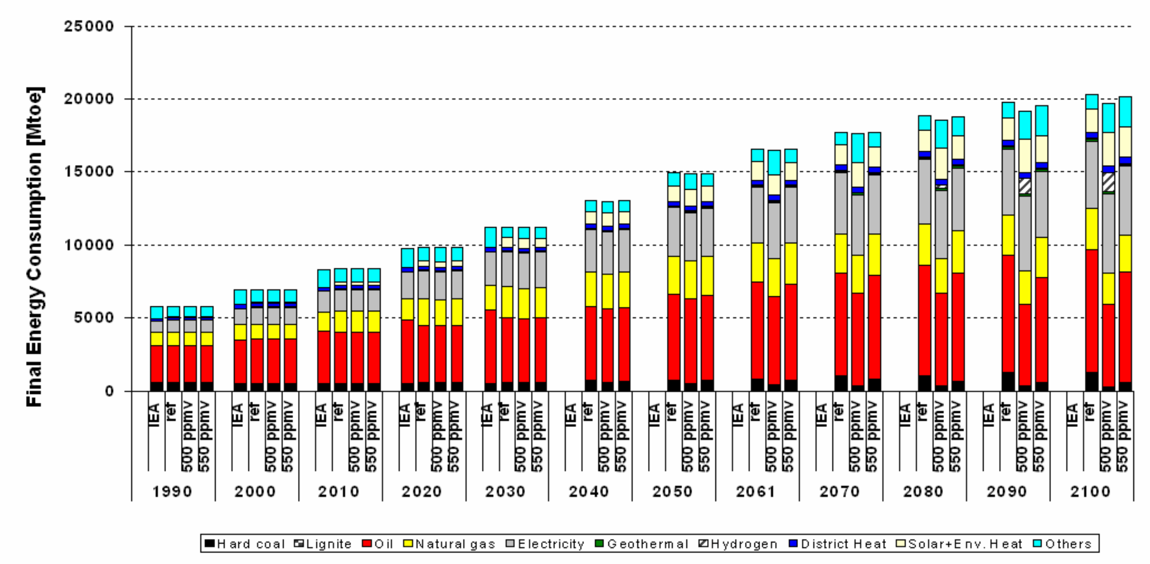

Figure 5-26: Change in structural energy demand of total final energy consumption

The power generation increases around 17% for the case of 500-ppmv stabilization and 1.8% for the 550-ppmv stabilization compared to the base case. Electricity production decreases from fossil fuels (hard coal, lignite, oil, etc.) and the production increases from low emitting fuels (natural gas), non-emitting fuels (nuclear and hydro) and renewable (biomass, biogas, waste, solar, wind and geothermal). Electricity production from fusion technology takes place towards the end periods (see Figure 5-27). In the climate stabilization case, carbon free electricity production increases around 1.8 times in 550-ppmv and 2.5 times in 500-ppmv stabilization case, towards end period of the model horizon compared to base case. Likewise fossil fuels reduce around 35% in 500-ppmv case and 23% in 550-ppmv stabilization case compared to base case. Electricity demand increases by regions and by sectors for the switching of the high carbon energy carriers to non-carbon energy carriers. Net electricity generation capacity increases around 11% in 550-ppmv and 33% in 500-ppmv stabilization cases compared to the value of base case towards the end periods of the model horizon (see Figure 5-28). Such high increase rate of the capacity is due to the low utilization of the technologies like biomass, waste, biogas, wind, solar and hydro power plants. The overall utilization rate remains around 59% towards the end periods of the model. In climate stabilization cases the CO_2 free learning technologies penetrate more, i.e., wind onshore and wind offshore for electricity production and geothermal heat pump in end use sector. Technologies like biogasification, solid oxide fuel cell and molten carbonate fuel cell does not selected by the model.

Primary energy consumption increases in the case of climate stabilization cases of 550-ppmv and 500-ppmv compared to the base case. The increase in primary energy is maximum circa 10% towards the end periods as compared to the base case. Increase in primary energy arises for more production of the electricity that is used in the end use sectors for which the overall efficiency of the fuel decreases. Also the integration of inefficient fuel in the electricity production sector increases in the primary energy demand. In primary energy consumption, hard coal, lignite and oil decrease compared to the base case. Nuclear, deuterium, lithium, hydro, wind, solar, geothermal and others (biomass, waste and biogas) increase in the power generation sector. Primary energy consumption increases for all the regions in TIMES G5 model (see Figure 5-29).

Carbon dioxide production reduces in all regions in the climate stabilization scenarios (see Figure 5-30). Carbon sequestration technologies are selected across different regions. The sequestred carbon dioxide goes for dumping. All regions select carbon dioxide sequestration technologies towards the end periods of model horizon. The technologies selected are IGCC and CCGT technologies with CO_2 sequestration facility. Hydrogen production from natural gas having carbon sequestration facility technology is selected towards the end periods. In case of 500-ppmv, the CO_2 sequestration technologies are selected from the period 2055 onwards and for 550-ppmv, the selection starts from 2080 onwards (see Figure 5-31). The fuel switching for the case of 500-ppmv starts from 2005 onwards and for the case of 550-ppmv starts from 2015 onwards. The ppmv CO_2 concentration in the atmosphere for the base case and climate stabilization scenarios is shown in Figure 5-32. The track of atmospheric CO_2 concentration of 550-ppmv changes with respect to base case from 2020 onwards and for 550-ppmv it is 2030.

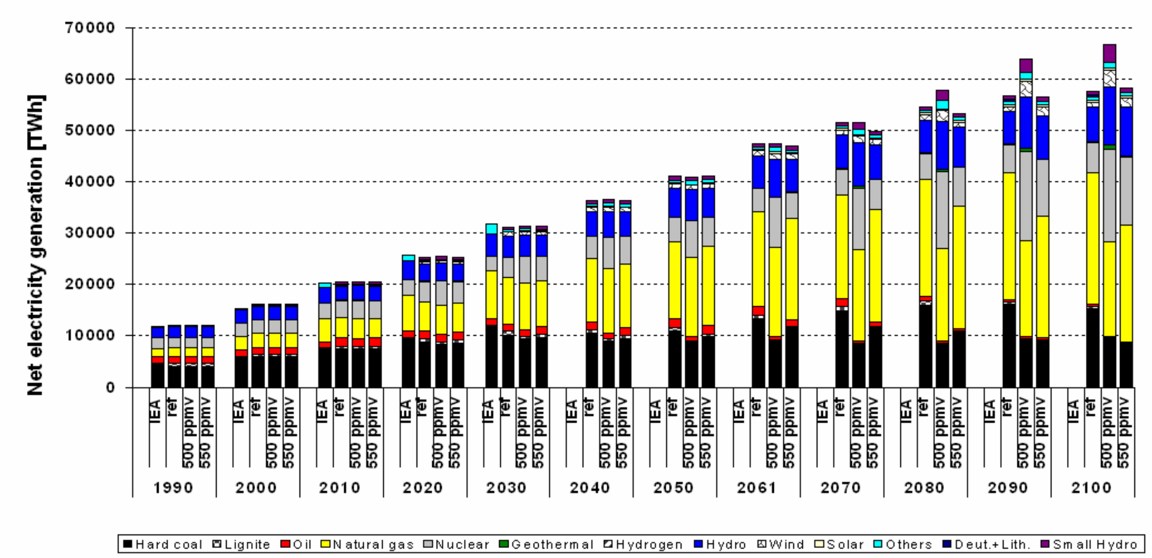

Figure 5-27: Electricity production by energy carriers

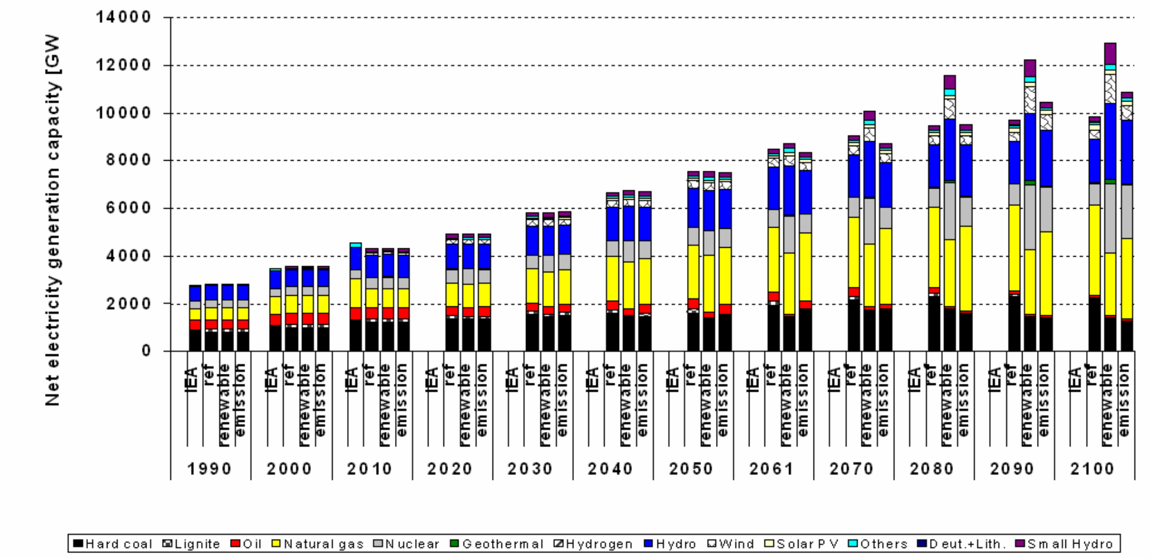

Figure 5-28: Electricity generation capacity by energy carriers

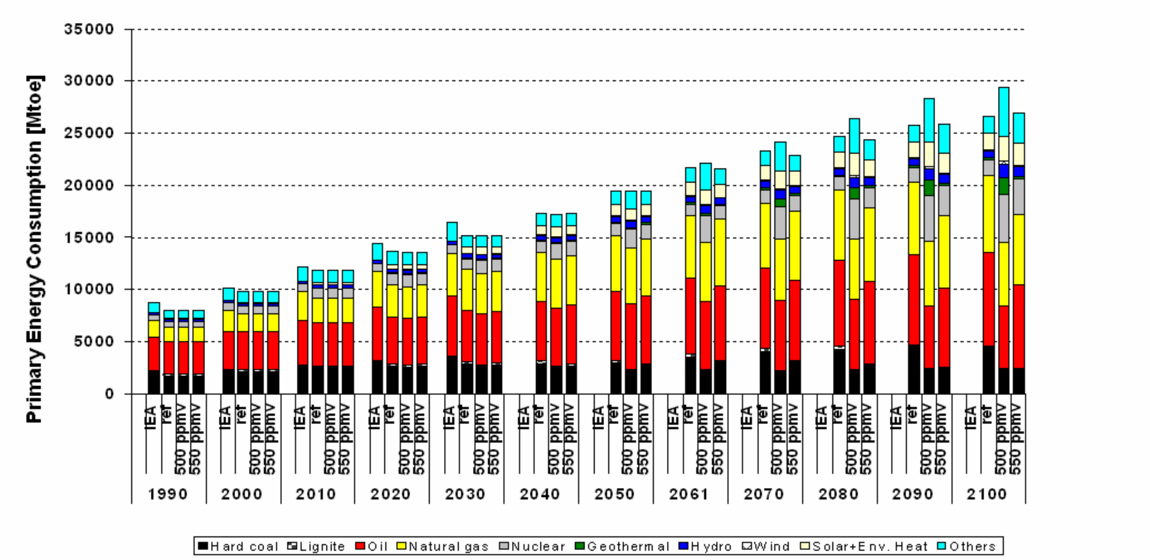

Figure 5-29: Primary energy consumption

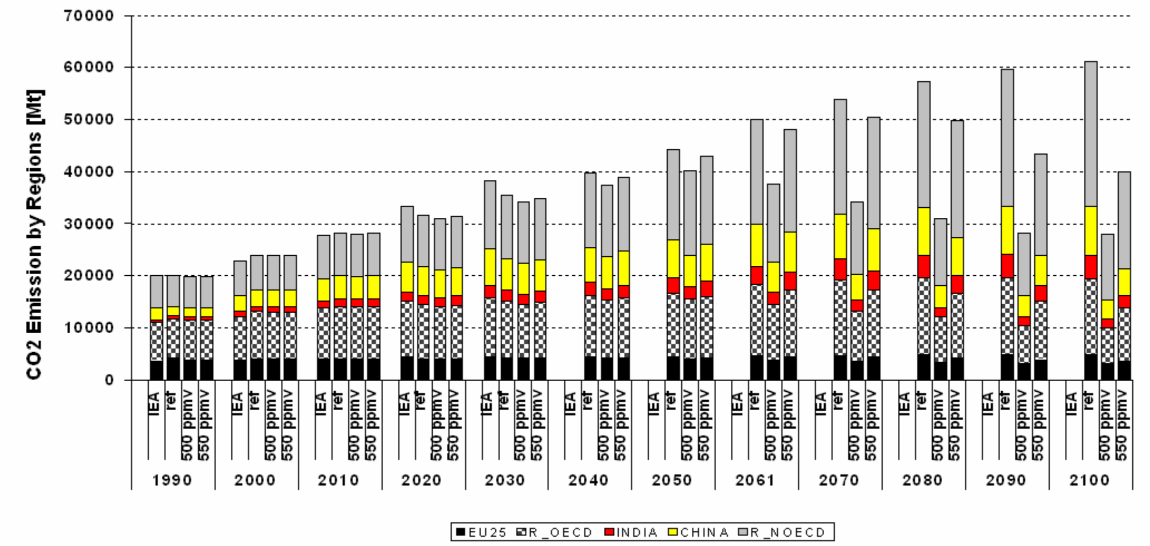

Figure 5-30: CO_2 emission by regions

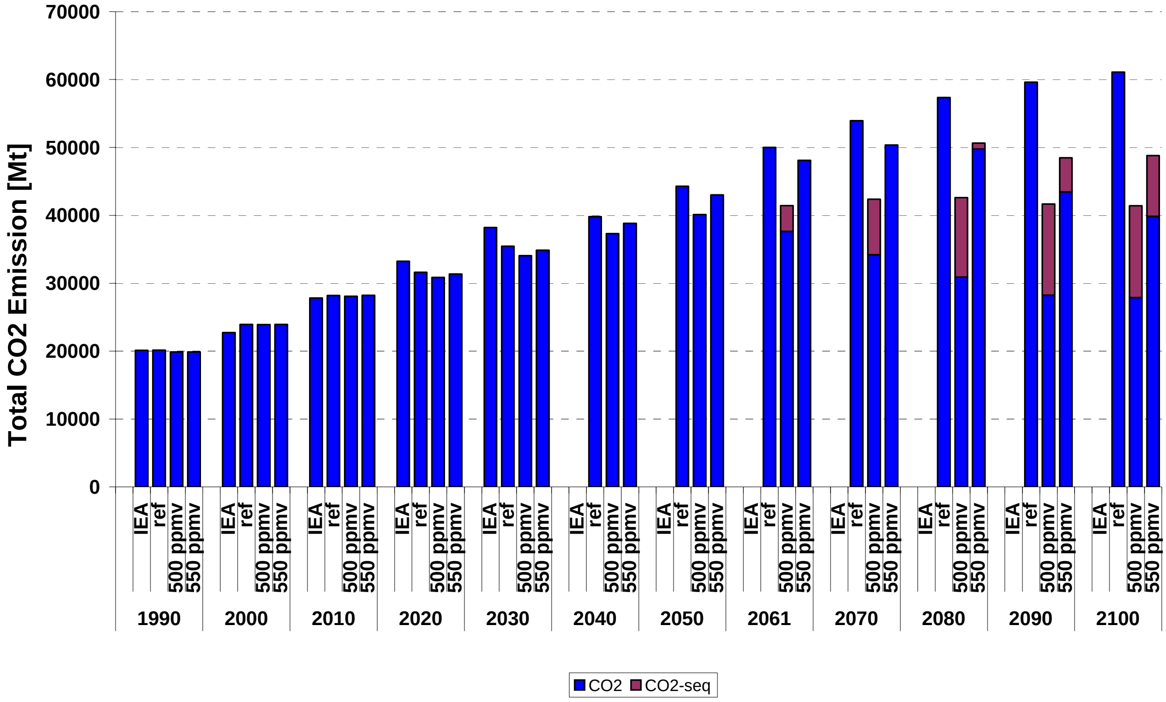

Figure 5-31: Total CO_2 and sequestered CO_2 emission in different scenarios

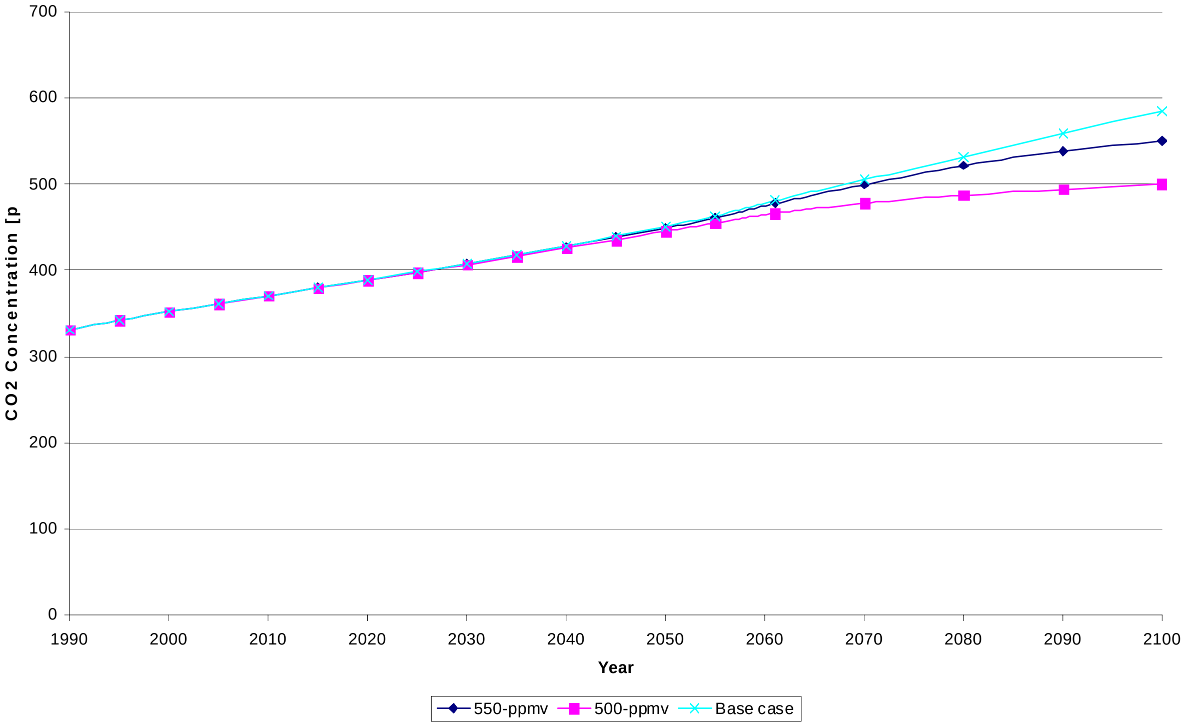

Figure 5-32: CO_2 concentration in the atmosphere in different scenarios

The atmospheric temperature rises upto 2.41°C and deep ocean a layer upto 0.33°C till 2100 in the climate stabilization cases.

5.2.1.6 Summary and conclusion of the base case and CO_2 stabilisation case

In total final energy consumption, the share of commerce sector energy consumption remains approximately constant from first to last period of the model. Coal, oil and natural gas reduce their market share to a small margin from initial to final period. However, electricity, renewable, environmental heat, hydrogen and synthetic fuel gain sizable market shares. Biomass utilization in residential sector decreases in future periods and in commerce sector, its use remains in a stable value but in industry sector the use of biomass increases. Geothermal and solar energy penetrates in all sectors. RME, methanol, ethanol and hydrogen enter inside the transport sector to a certain margin. Natural gas in electricity production sector increase its share and hold highest share among all energy carriers towards the end periods. Coal, nuclear, oil, large hydro and geothermal reduce their market shares in electricity production towards final periods compared to initial. Energy carriers like natural gas gains maximum share in electricity production towards the end periods compared to other share gaining energy carriers. Small hydro, solar PV, wind energy and others (biomass, biogas, hydrogen and waste) gain considerable market share due to the minimum market share allocated to them in different sectors like electricity and heat production, transport, residence sector, etc.

Among technologies CCGT and IGCC penetrates highly inside the electricity production sector reaching to its maximum value provided by periods. Coal and gas based CHP plants enters more in EU25, R_OECD, R_NOECD and China energy system, as these regions need more centralized heat for their heating system, whereas India integrate more condensing coal plants and gas turbines. Extraction condensing CHP plants enter more in cold climate regions that hot climate regions. Advance nuclear based CHP and electricity plants integrate in different regions differently. The capacity and electricity production from nuclear plants around world increases more than three times in-between the initial and final periods of the model. Waste based technology, biogas based power-producing technology, wind onshore and wind offshore penetrate to certain margin for fulfillment of the minimum renewable electricity shares in each region.

In primary energy consumption coal, oil, nuclear and others loose their market share and natural gas, hydro, wind, solar and geothermal gain market shares from starting to end period of the model.

Due to decrease in market share of polluting energy carriers the proportion of the emission of CO_2 reduces in future periods. The emission figure inside this global model refers approximately to the value of 590 ppmv atmospheric CO_2 concentration in 2100 (with assumption that all CO_2 emission from the model is exposed to the atmosphere).

In climat estabilisation of 500-ppmv and 550-ppmv test, sectoral energy demand decreases and also total final energy demand. Efficient, low and non-polluting fuels integrate more inside the sectoral energy demand in the climate stabilization cases. Electricity production, electricity generating capacity and primary energy consumption increase in these scenarios compared to base case and the capacity utilization reduces. IGCC and CCGT technologies with CO_2 facility are selected in these scenarios run. More nuclear and renewable technologies are selected in climate stabilization cases compared to base case. Hydrogen production from natural gas with carbon dioxide sequestration facility is selected in the stabilization cases. Fusion technology and fuel cells enter inside the sectoral energy demand in stabilization cases. Fuel switching from 2005 onwards takes place in the climate stabilization cases and carbon free electricity production increases in the stabilization cases. The CO_2 production by regions, by fuels and by sectors reduces in stabilization cases. The change in temperature level of the atmosphere and deep ocean layer observed during this test. The atmospheric temperature rises to the upper value of 2.41^{o}C in year 2100 and the temperature of deep ocean layer rises to the upper value of 0.33^{o}C in year 2100.

5.2.2 Uncertainty in learning rates in global learning scenarios

Uncertainty in learning rates has been tested in different learning domains, i.e., at first on global learning without time lag and knowledge gap concept; global learning with knowledge gap concept; and global learning with knowledge gap and time lag concept. The domain of each learning scenarios are presente below sequencially.

Some notation used on learning scenarios result analysis is given here for easy understanding. Min, Med and Max stands for minimum Progress Ratio (PR), medium PR and maximum PR. Some time it is also defined directly as MinPR, MedPR and MaxPR. In some cases it is defined like MinIGCC that implies IGCC technology on minimum PR. In some scenarios the short code defined as MedPRKL (medium PR knowledge lack/gap) and MedPRTL (medium PR time lag). Also technology basis it is defined as MedTLWON, which means medium PR of wind offshore technology. Short code of some technologies used for result analysis is: BIOG (biogasification, SOLPV is for solar PV, WON is for wind onshore, WOF is for wind offshore and GEO is for geothermal HP).

5.2.2.1 Global learning scenario without knowledge lack and time lag concept

- **Comparison of the objective values**

The objective value of the three learning scenarios with maximum, medium and minimum progress ratio varies considerably showing that the cost development of the learning technologies. Objective value is maximum for maximum progress ratio (lowest learning rate) followed by medium and minimum progress ratio (highest learning rate) and the values respectively are 303468.4 B€(00), 303506.1 B€(00) and 303525.1 B€(00). The objective value of the reference case (303495.2 B€(00)) is above than the scenario of minimum PR and below to the objective value of medium and maximum PRs. All the objective values are nearly equal with each other with very significant difference among them. The difference in objective value in global learning scenarios with uncertainty in learning rates and the base case arises from many angels. Firstly the learning investment required for the learning technologies those start from initial higher investment cost in learning scenarios as compared to base case. With initial specific cost of the same technology, the value of learning investment is different for different learning rates. The learning investment arises for the difference in the starting point of the investment cost in learning scenarios and the base case, e.g., wind offshore has investment cost of 1245 €(00)/kW in period 1990 taken inside the database but in case of learning scenarios, it starts from 1750 €(00)/kW. Therefore to reach from the investment cost 1750 €(00)/kW to 1245 €(00)/kW, it needs some learning investment and this learning investment depends on the learning rates. For higher learning rate, it is high and for lower learning rate, it is low. Secondly the development of periodwise investment cost in both learning scenarios and inside the base case varies. Thirdly the floor cost of some technologies is different in different learning rates. Higher progress ratio has higher floor cost and lower one has low for technologies, e.g., wind offshore. Fourthly, the minimum renewable electricity production from renewable learning technologies forces the learning technologies to produce the electricity irrespective of the higher learning investment subject to learning rates. Thus the objective value depends on all the above mentioned factors.

- **Specific cost development of the learning technologies**

The specific cost development of the learning technologies on global learning concept without knowledge lack and time lag concept is shown in the Figure 5-33. All learning technologies attain their floor cost within the model horizon. IGCC and CCGT technologies reaches to their floor cost respectively 900 €(00)/kW and 375 €(00)/kW in the year 2040 for all the progress ratios (see Table 3-2). Solar PV reaches to the floor cost 2100 €(00)/kW in the year 2025 for low PR, 2040 for medium PR and 2061 for high PR. Likewsie wind onshore, wind offshore and geothermal heat pump reaches to their floor cost in different periods for different PRs, those are depicted in Figure 5-33.

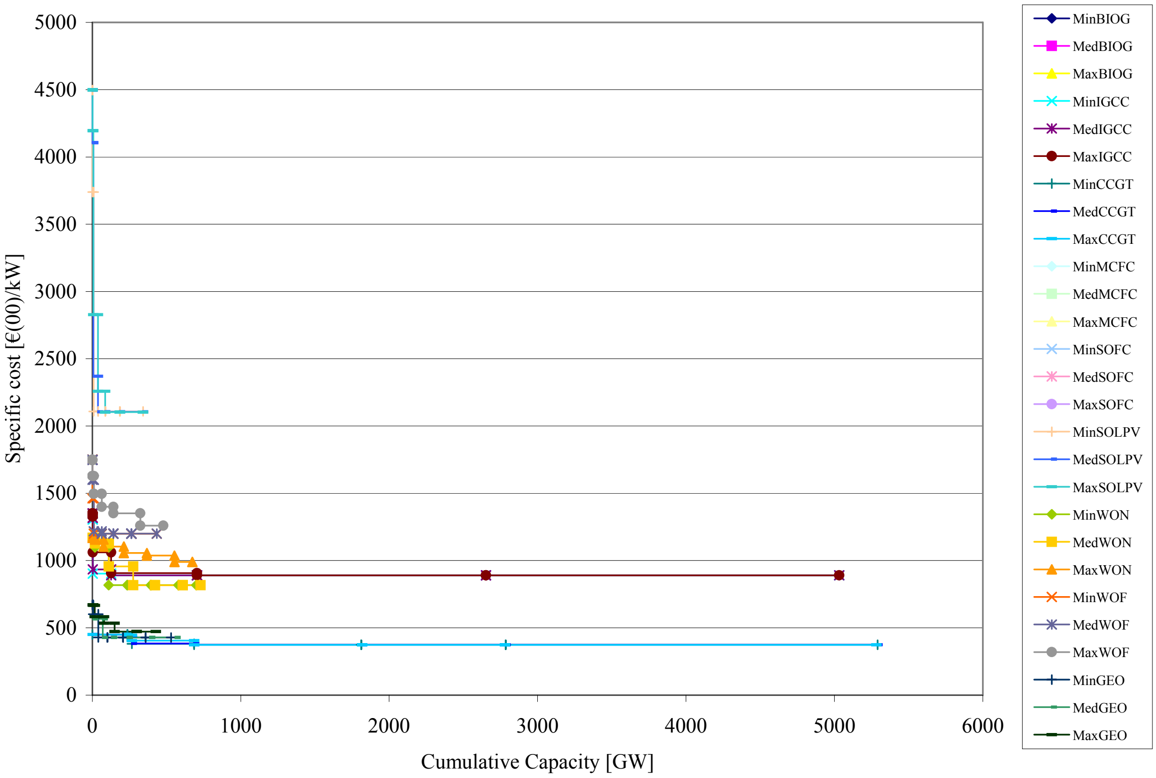

Figure 5-33: Specific cost development of learning technologies for world

- **Cumualtive capacity development across the globe**

Cumulative capacity development has been observed different among the different learning scenarios of global learning (without knowledge lack and time lag) and also in the base case. Cumulative capacity of IGCC and solar PV technology remain approximately same on global level in all scenarios as depicted in Table 5-4 because the IGCC development reaches to its maximum value and solar PV satisfy the minimum renewable electricity production. Cumulative capacity development of wind offshore remains same in all scenarios. Combined cycle gas turbine penetrates more in learning scenarios compared to base case for the advantage of global learning. The highest penetration is observed in case of minimum PR followed by descending in order of medium and maximum PRs. Wind onshore follows the same structure like CCGT technology. Geothermal heat pump introduce differently for different PRs due to the selection of different values of new capacity in different periods corresponding to the cost comparison among technologies those are available in the same period. The uncertainty in learning rates has effect on CCGT, wind onshore and geothermal heat pump penetration across the world regions. Higher learning rate induces more penetration of any learning technology and lower learning rates shows the reverse phenomenon. The penetration of the learning technologies across world is depicted in Table 5-4.

Table 5-4: Cumulative capacity development of the learning technologies

Technology	Global Values			
	MinPR	MedPR	MaxPR	Base
Integrated gasification CC	5032.72	5032.72	5032.72	5031.57
Combined cycle GT	5291.04	5289.87	5283.91	5152.20
Solar PV	340.99	340.96	340.96	340.94
Wind on-shore	700.68	697.36	673.79	673.10
Wind off-shore	433.62	433.62	432.38	432.32
Geothermal HP	530.00	559.79	427.86	339.70

In case of learning scenarios, the penetration is little bit in higher side for the learning technologies due to the reduction of the cost in global learning. The maximum cumulative capacity development of IGCC technology is experience in all learning scenarios. IGCC technology is integrated more in global learning scenario across EU25, R_OECD, India and China energy system. CCGT technology integrates more across all regions and in all learning scenarios compared to the base case. Wind onshore integrates more inside the EU25 and R_OECD regions, whereas for R_NOECD, INDIA and CHINA, it remains same in all scenarios. Solar PV penetrates same in all scenarios across all regions. Geothermal heat pump enters more in all regions in learning scenarios compared to the base case. Cumulative capacity of learning technologies across globe is portrayed in Figure 5-34.

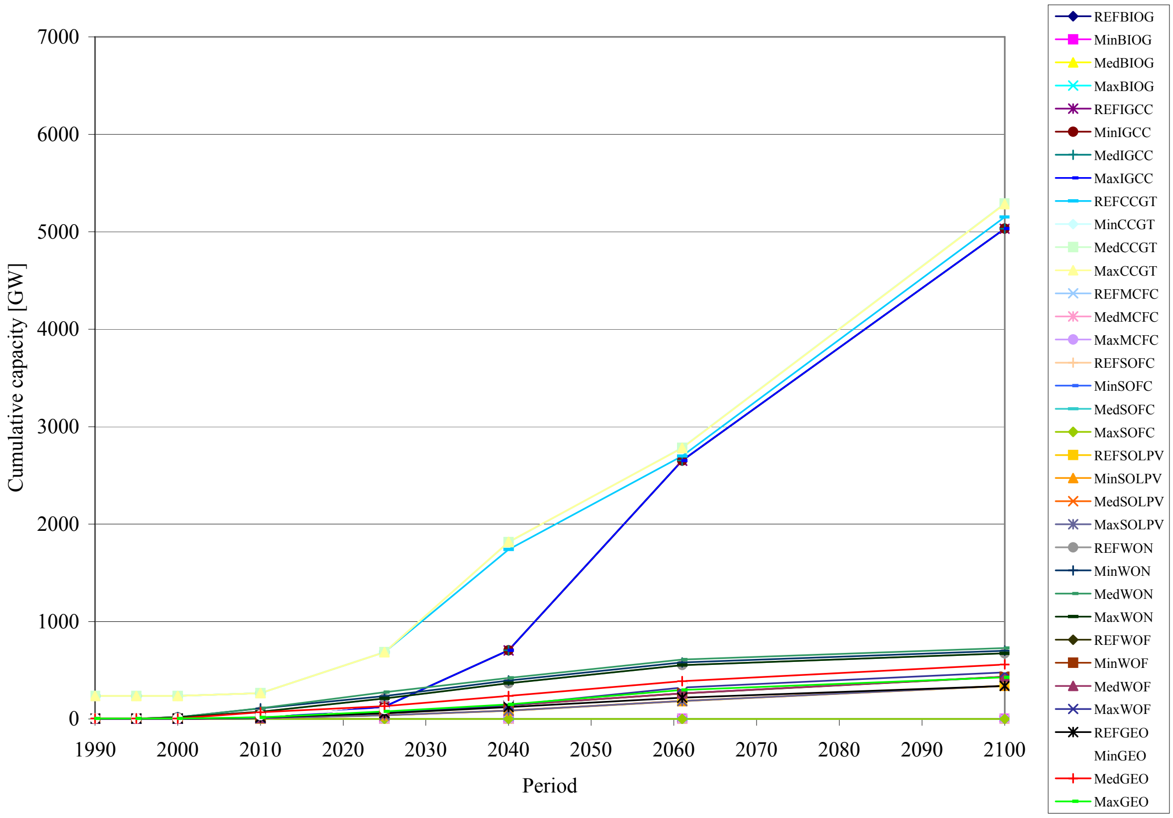

Figure 5-34: Cumulative capacity of global learning technologies by scenarios

- **Final energy consumption comparison by scenarios**

The final energy consumption by scenarios is depicted in the Figure 5-35 shows that the energy consumption increases in case of learning scenarios compared to base case. In total final energy consumption, district heat and (solar+env. heat) losses their market share, whereas coal, natural gas, electricity and geothermal gains their market share. The integration of inefficient fossil fuels and high penetration of geothermal heat pump increase the final energy demand. Electricity increases the market share as the cost of learning technologies decreases inside the global learning. The difference of the final energy consumption starts from 23 Mtoe in year 2010 to 85 Mtoe in year 2100, inbetween the learning scenarios and base case.

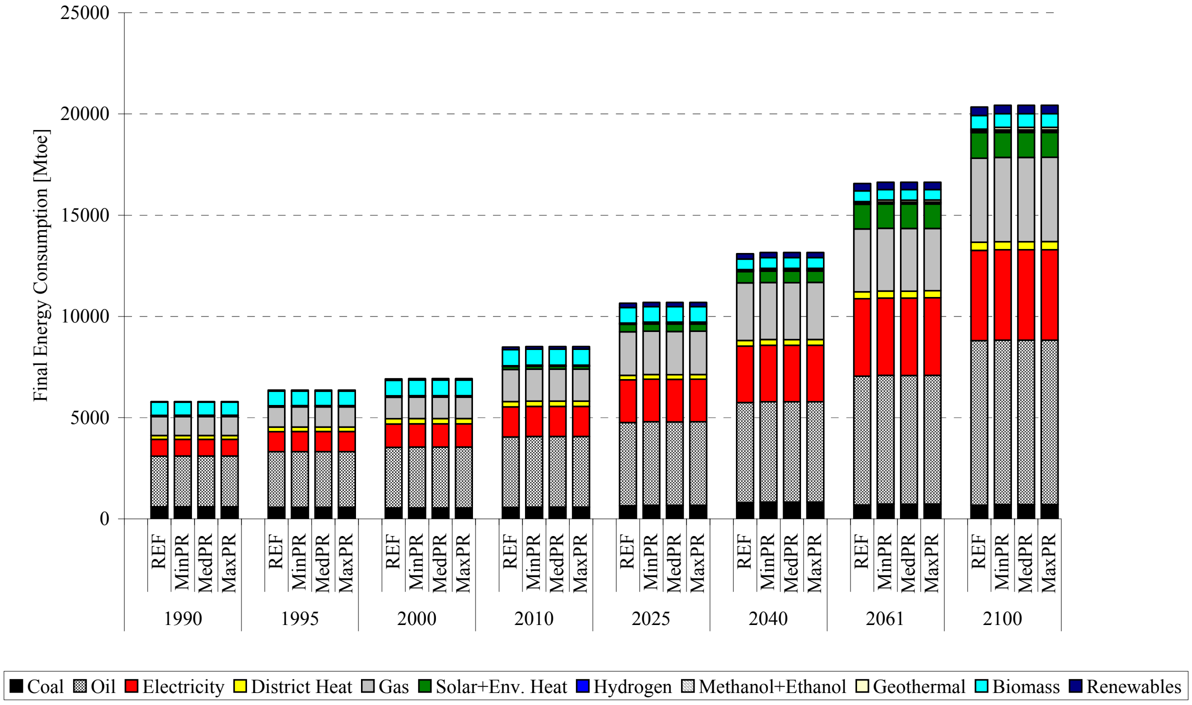

Figure 5-35: Final energy consumption comparison by scenarios

- **Electricity generation comparison by scenarios**

Electricity production from learning technologies in learning scenarios increases as compared to base case. The increase in cumulative electricity from learning technologies is highest for minimum PR and lowest in maximum PR. The cumulative electricity production and heat production from geothermal HP is provided in Table 5-5.

Table 5-5: Cumulative electricity and heat production from learning technologies

Cumulative electricity [TWh] and heat [PJ] production from learning technologies						
Scenario	Energy	Unit	MinPR	MedPR	MaxPR	Base
Coal	Electricity	[TWh]	43680	43680	43680	43680
Gas	Electricity	[TWh]	45997	45981	45929	44751
Solar	Electricity	[TWh]	959	958	958	958
Wind	Electricity	[TWh]	3693	3686	3601	3601
Geothermal	Heat	[PJ]	3258	3363	2652	2085

Total electricity production in learning scenarios increases compared to base case. The increase in electricity production starts from periods 2025 onwards. The difference of the electricity production within base case and learning scenarios is around 10 TWh in period 2025 and 100 TWh in period 2100. Electricity production from coal, natural gas and wind increases.

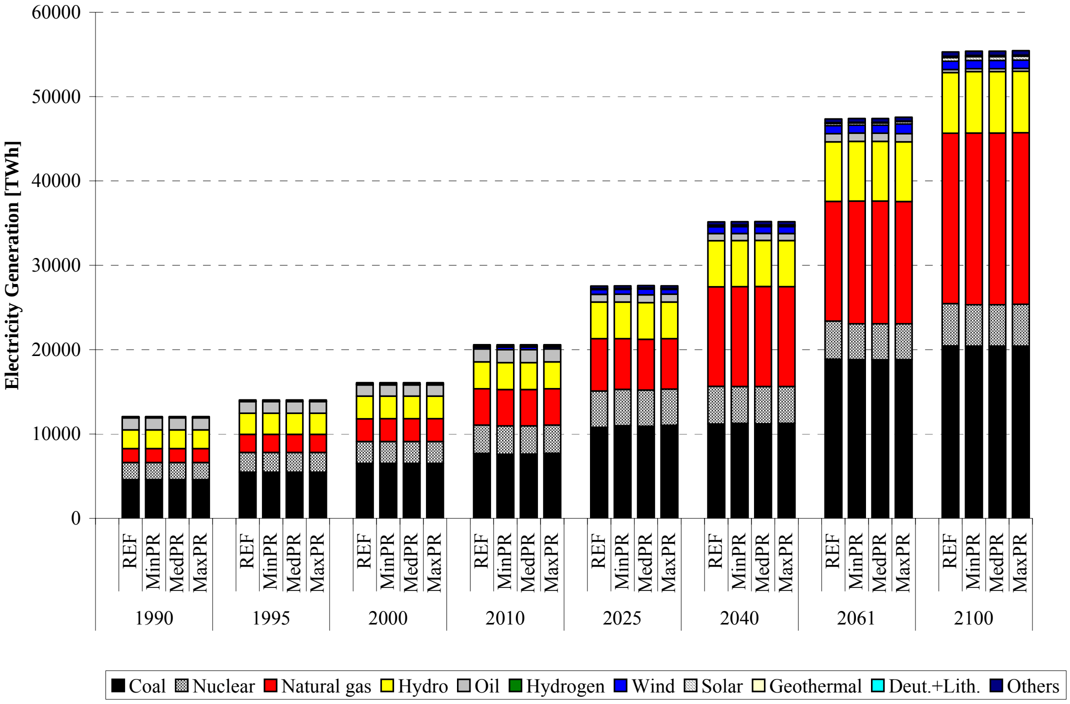

Figure 5-36: Electricity generation comparison by scenarios

- **Primary energy consumption comparison by scenarios**

The primary energy consumption increases in learning scenarios compared to the base case. Due to global learning the efficient energy carriers are phased out and the inefficient energy cariers enter, e.g., phase out of solar. The demand of energy carriers by periods and by scenarios is provided in the Figure 5-37. The variation of total primary energy consumption in comparison to learning scenarios is very less and also the difference between the reference case and the learning scenarios lie within 32 Mtoe from starting to end period of the model horizon. Also the increase in electricity production increases the primary energy consumption due to the decreases of overall efficiency.

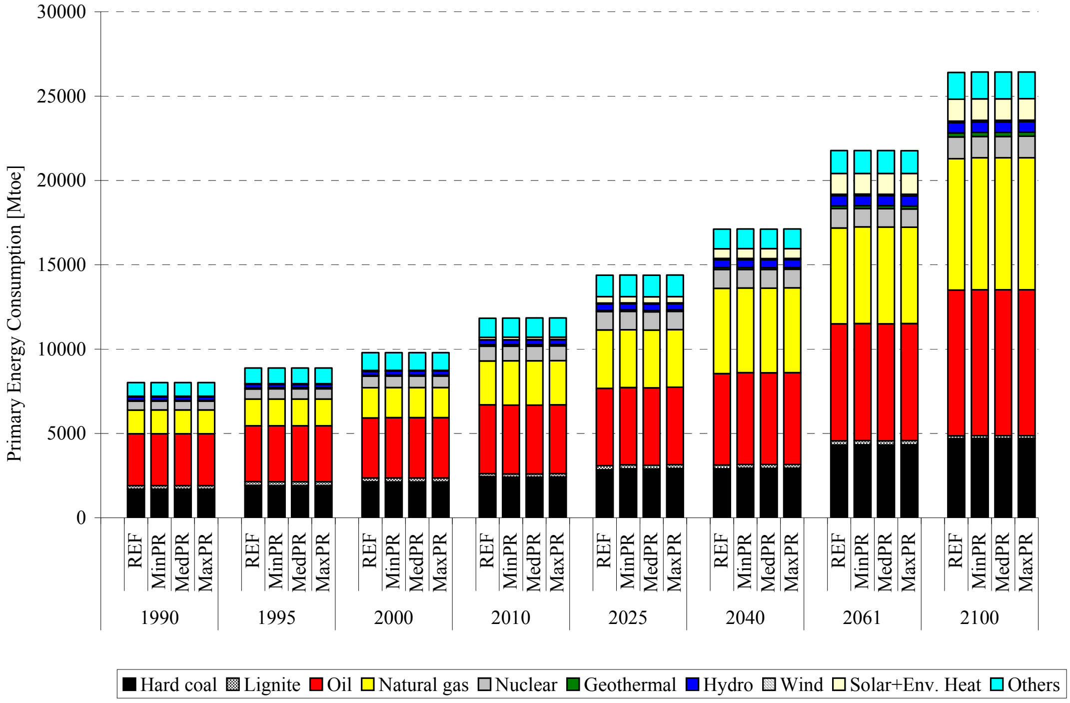

Figure 5-37: Primary energy comparison by scenarios

- **CO_2 emission comparison by scenarios**

The emission of CO_2 in reference case is in lower side compared to learning scenarios. The increase in CO_2 emission in learning scenarios is higher due to more penetration of CCGT technology inside the energy system for global learning effect. The difference of CO_2 emission between the learning scenarios and base case remains within the maximum value of 170 Mt till the end of model horizon as given in Figure 5-38.

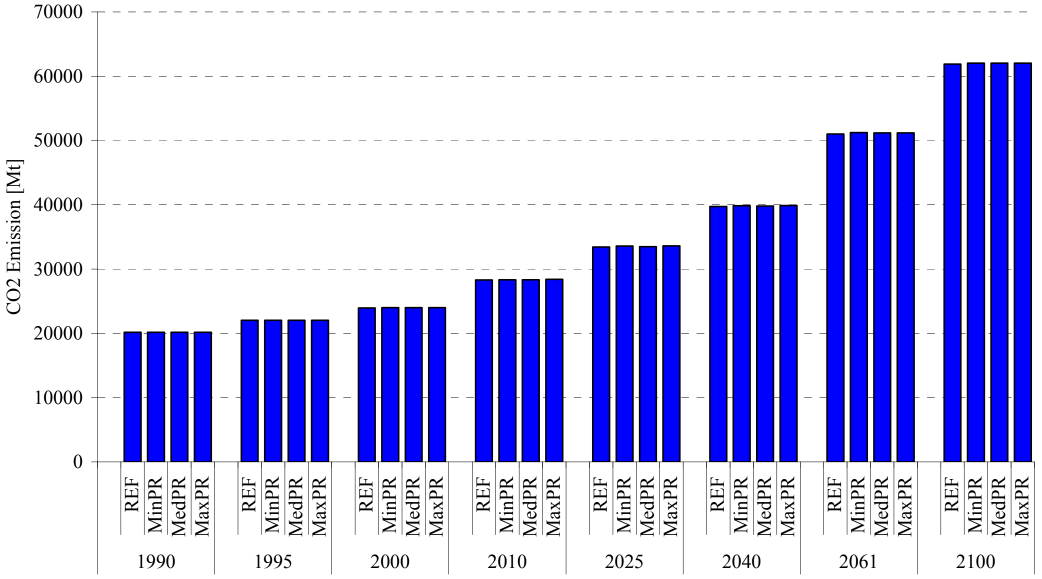

Figure 5-38: CO_2 emission comparison by scenarios

5.2.2.2 Global learning scenario with knowledge gap concept

- **Comparison of objective values of reference and knowledge gap scenarios**

The objective value of the three learning scenarios with maximum, medium and minimum progress ratio varies considerably showing that the cost development of the learning technology changes with respect to the learning rates. Objective value is maximum for maximum progress ratio (lowest learning rate) followed by medium and minimum progress ratio (highest learning rate) and the values respectively are 303512.0 B€(00), 303531.4 B€(00) and 303590.5 B€(00). The objective value of the reference case (303495.2 B€(00)) is in lower side compared to all the learning scenarios. The increase in objective value of the learning scenarios arises for the additional cost imposition by the knowledge lack regions on the learning technology utilization.

- **Specific cost development of the learning technologies**

Biogasification, IGCC, CCGT, molten carbonate fuel cell, solid oxide fuel cell, solar PV, wind onshore, wind offshore and geothermal heat pump are considered for global learning and out of these five technologies are considered for the global learning with technology gap in terms of higher specific cost, i.e, IGCC, CCGT, solar PV, wind onshore and wind offshore. Rest four technologies learn globally without knowledge gap, i.e., biogasifications, molten carbonate fuel cell, solid oxide fuel cell and geothermal HP. The specific cost of the biogasification, solid oxide fuel cell and molten carbonate fuel cell does not change with respect to time, as the model does not select any of these technologies to produce energy for their high learning investment cost. Also there is no market share provided for these technologies inside the model to be utilized. For developed regions, the IGCC technology reaches its floor cost in the period 2040 by the minimum and medium progress ratio scenarios, whereas in case of high progress ratio, it reach to the floor cost in period 2061. The diffusion of the IGCC technology remains same in all the three scenarios of different progress ratios by reaching its upper limit of the new capacity development given by periods. Combined cycle gas turbine reaches the floor cost in the period 2040 for all the progress ratios. In case of lower progress ratio, the capacity deployment is little bit in higher side compared to others two. Solar PV attains floor cost in the period 2040 for minimum and medium progress ratio, whereas for higher specific cost, it reachs to floor cost in the period 2061. The cumulative capacity development more or less remains same in different learning scenarios. Wind onshore reaches to floor cost in the period 2040 for minimum and medium PRs; and 2100 for maximum PR. Wind offshore reaches to floor cost in the period 2025 for minimum and medium progress ratios. In case of minimum progress ratio and medium progress ratio, the geothermal heat pump reaches to floor cost in the period 2040 and 2061 respectively and does not attain the floor cost in case of maximum progress ratio (see technology floor cost Table 3-2).

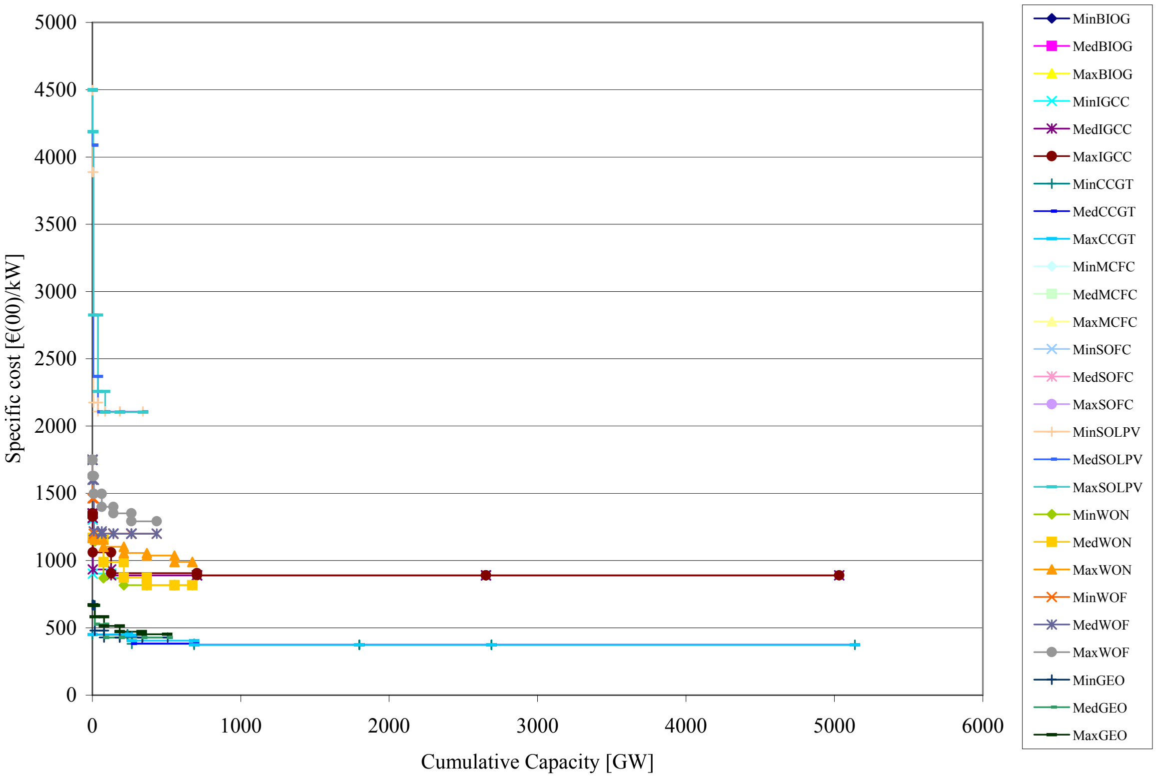

Figure 5-39: Specific cost development of technologies for developed regions

The specific cost of the technologies for the knowledge lack regions remain always in higher side compared to developed regions for the same learning technology (see Figure 5-40). The specific cost ratio between developing and developed regions for different learning technologies lies in between 1 to 1.16, i.e., the specific cost of the same technology is higher, maximum upto 1.16 times for developing regions compared to developed regions, if they are going to use the same technology in same time period. The difference of the specific cost between developed and developing regions reduces with more adaptation of the learning technologies.

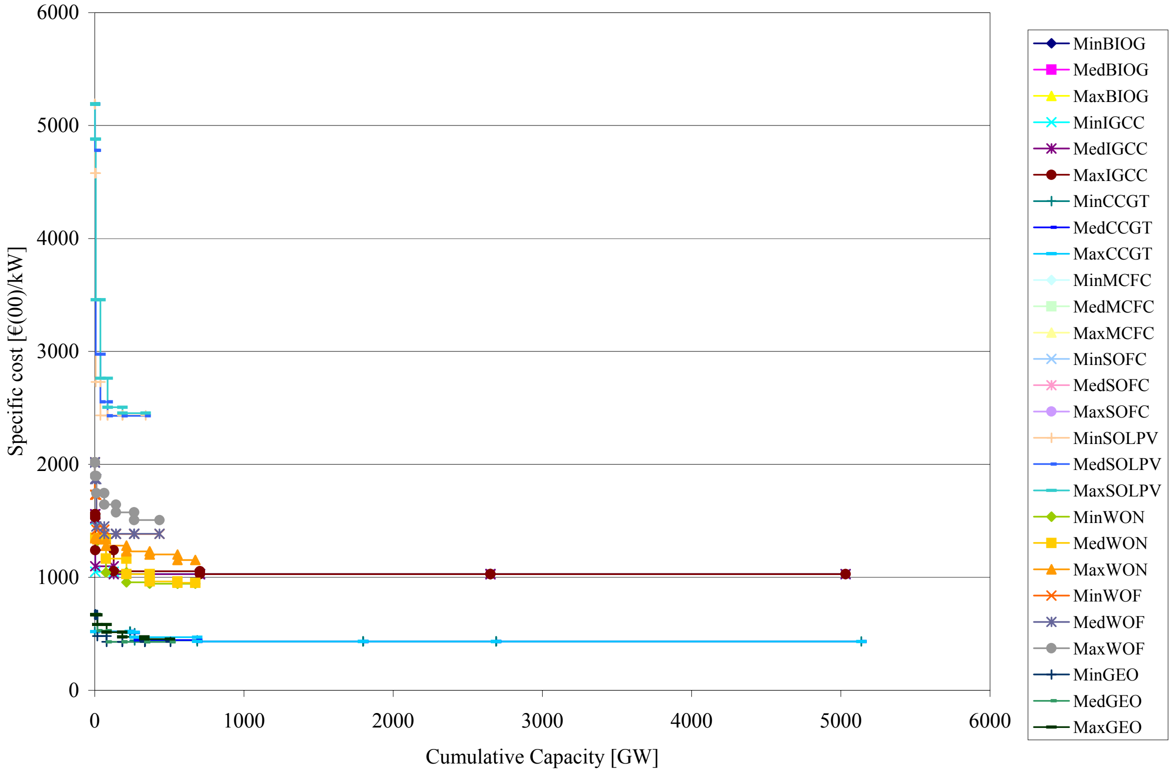

Figure 5-40: Specific cost development of technologies for developing regions

The specific cost of the technologies like bio-gasification, solid oxide fuel cell and molten carbonate fuel cell does not change irrespective of the time periods. The specific cost of IGCC, CCGT, solar PV, wind onshore, wind offshore and geothermal heat pump for developed regions in the period 2000 are respectively 1350, 450, 4500, 1170, 1750, 670 €(00)/kW and corresponding values of developing region are 1557, 519, 5189, 1348, 2019 and 670 €(00)/kW. The specific cost of the technologies in period 2025 attains the figure of 966, 390, 2456, 987, 1304 and 529 €(00)/kW for developed regions for respective technologies, and for developing regions the figures touches to 1129, 451, 3059, 1162, 1543 and 529 €(00)/kW. With same sequence of the technologies, the attainment of the specific cost in period 2061 is 890, 374, 2106, 890, 1250 and 443 €(00)/kW for developed regions, whereas for developing regions, it is 1027, 431, 2457, 1036, 1448 and 443 €(00)/kW. The specific cost difference between developed and developing regions decreases from the starting to end period, e.g., in case of wind offshore the difference is 269 €(00)/kW in 2000 reduces to 194 €(00)/kW in the period 2100. Likewise for other technologies the investment cost reduction takes place but the reduction is highest for solar PV technologies, which has been observed inside the study due to the selection of learning parameters for which low value of cumulative capacity development drags the specific cost reduction to a high value. This provides the incentive for the developed and developing regions to utilize the technology more.

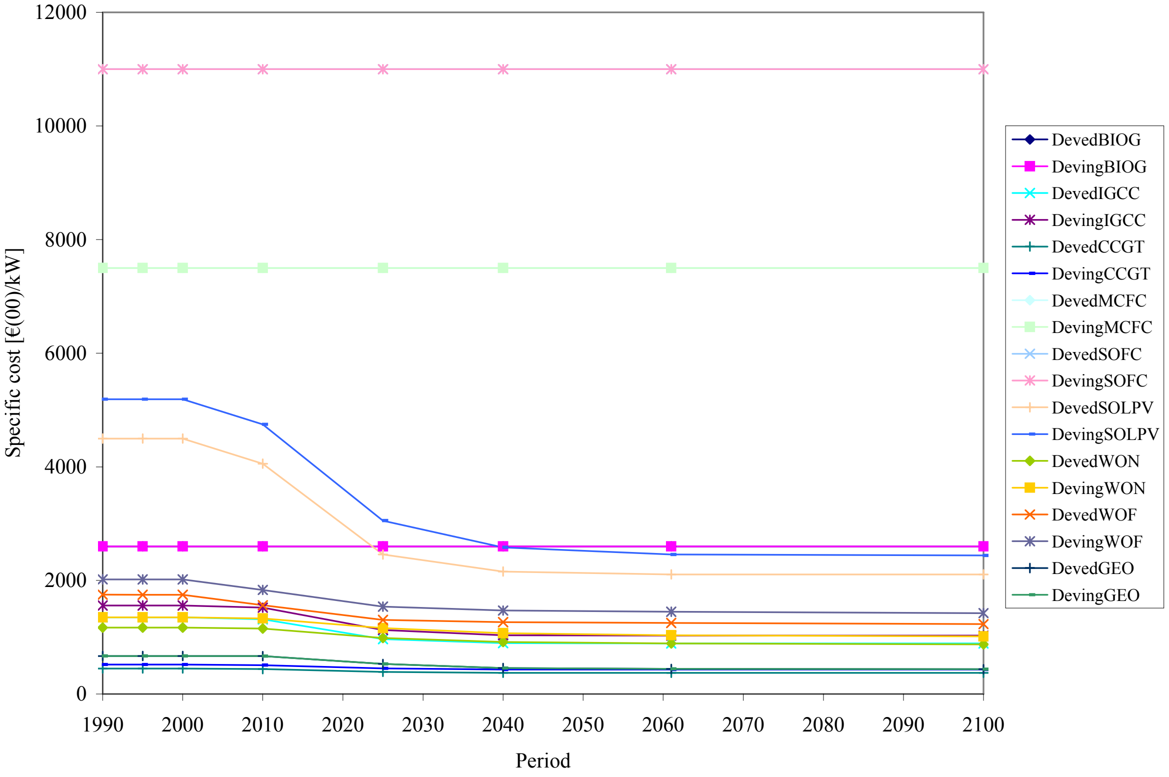

Figure 5-41: Specific cost development of learning technologies across regions (Note: Deved stands for developed regions and Deving stands for developing regions)

- **Cumulative capacity development of learning technologies**

There is very small difference in cumulative capacity development observed in case of different progress ratios in manufacturing region of global learning subject to knowledge gap approaches. Generally the learning technology development is in higher side for the low and medium progress ratios, compared to higher progress ratio. The penetration of IGCC, solar PV, wind onshore and wind offshore development in the manufacturing region remains more or less same. The development of the CCGT technology is in lower side in learning scenarios compared to the base case due to the additional cost imposed on developing region for the reason of knowledge lack. But the development of the geothermal heat pump is in higher side in learning scenarios as the knowledge gap is not applied to geothermal heat pump. The penetration of the geothermal heat pump is more in minimum progress ratio and diffusion of the technology decrease with increase in the progress ratio. Highest progress ratio has negative impact in technology selection on future technology development. The development of learning technologies around world by scenarios is provided in the Table 5-6.

Table 5-6: Cumulative capacity development of the learning technologies

Technology	Global Values			
	MinPR	MedPR	MaxPR	Base
Integrated gasification CC	5032.72	5032.72	5032.72	5031.57
Combined cycle GT	5138.13	5138.13	5138.13	5152.20
Solar PV	341.02	341.02	341.02	340.84
Wind on-shore	673.88	673.88	673.88	673.10
Wind off-shore	433.62	433.62	433.62	432.32
Geothermal HP	507.00	507.00	503.71	339.70

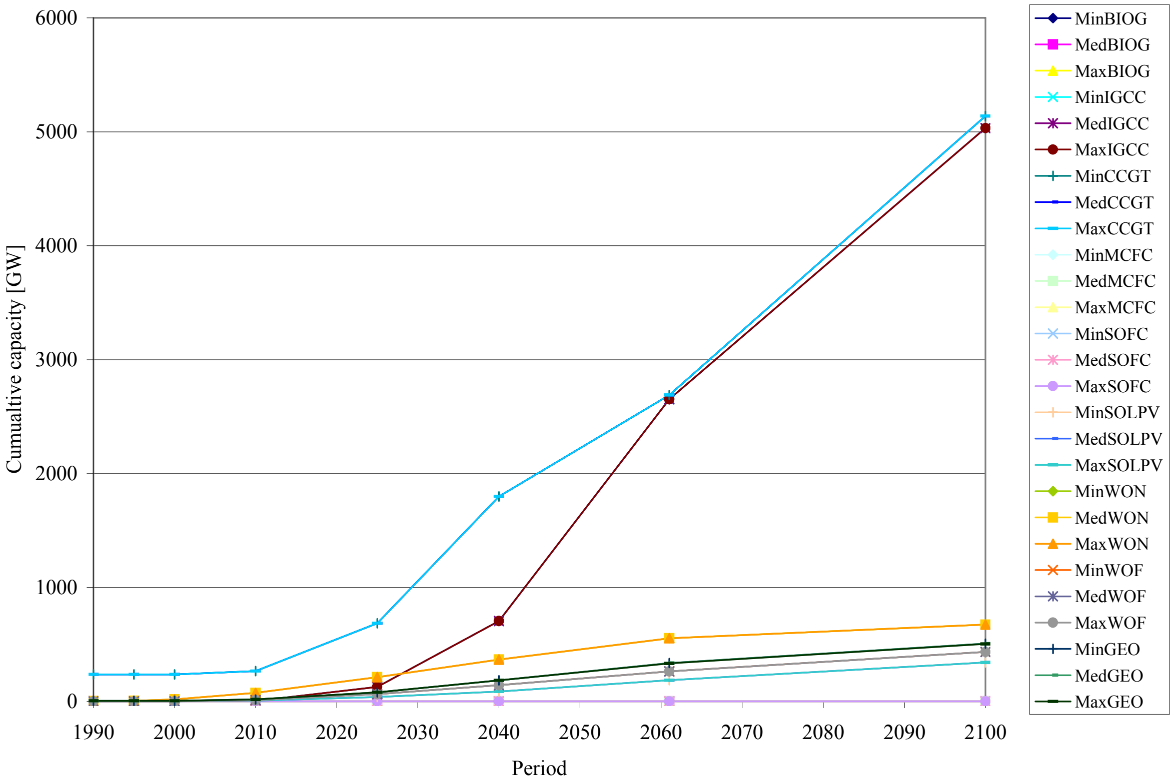

Figure 5-42: Cumulative capacity development of global learning technologies

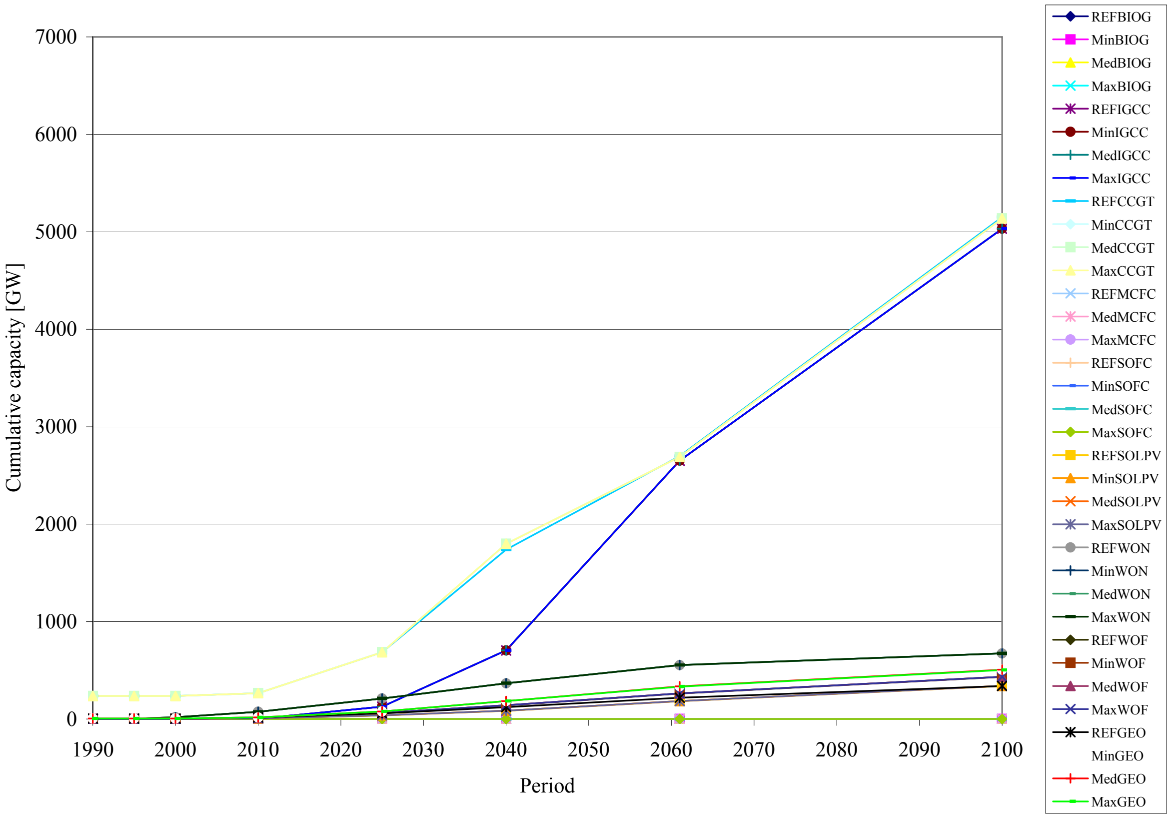

Figure 5-43: Cumulative capacity of manufacturing region by scenarios

The cumulative capacity of the learning technologies likes wind onshore, wind offshore and solar PV technologies remain same in all scenarios and across all regions. The integration of IGCC technology is more in learning scenarios compared to base case in EU25 and R_OECD. These regions get the benfit of global learning. But R_NOECD India and China regions use more IGCC in base case compared to learning scenarios, as the cost incurred for the knowledge gap approach of global learning is more. Due to knowledge gap the penetration of the CCGT technology across the R_NOECD region is less in learning scenarios compared to base case. For other regions, the penetration is some extent in higher side but the overall summation of the learning technologies remains below the base case. Geothermal heat pump selected more in learning scenarios across all regions. Solar PV, wind onshore and wind offshore penetrate equal in all scenarios across all regions.

- **Final energy consumption comparison by scenarios**

The final energy consumption by scenarios is depicted in the Figure 5-44 shows that the energy consumption increases in case of learning scenarios compared to base case. In total final energy consumption electricity and district heat loose their market share marginally, whereas coal, oil, gas, geothermal and biomass increase their market share. Electricity decreases the market share as the cost of learning technologies increases inside the developing regions. The decrease of electricity influences the selection of other technologies to fulfil the useful energy demand in end use sectors, i.e., for cooling, coking and heating useful energy demand. Therefore inefficient technologies are selected to raise the final energy demand. Also the environmetal heat associated with the heat pump is more, except electricity operated heat pump. Increase of geothermal heat pump increases the final energy demand, as environmental heat is associated with the technology in modeling paradigm. This increases the use of total final energy consumption marginally. The decrease of total final energy demand of base case in comparison to learning scenarios ranges from 23 Mtoe in year 2010 to 108 Mtoe in year 2100.

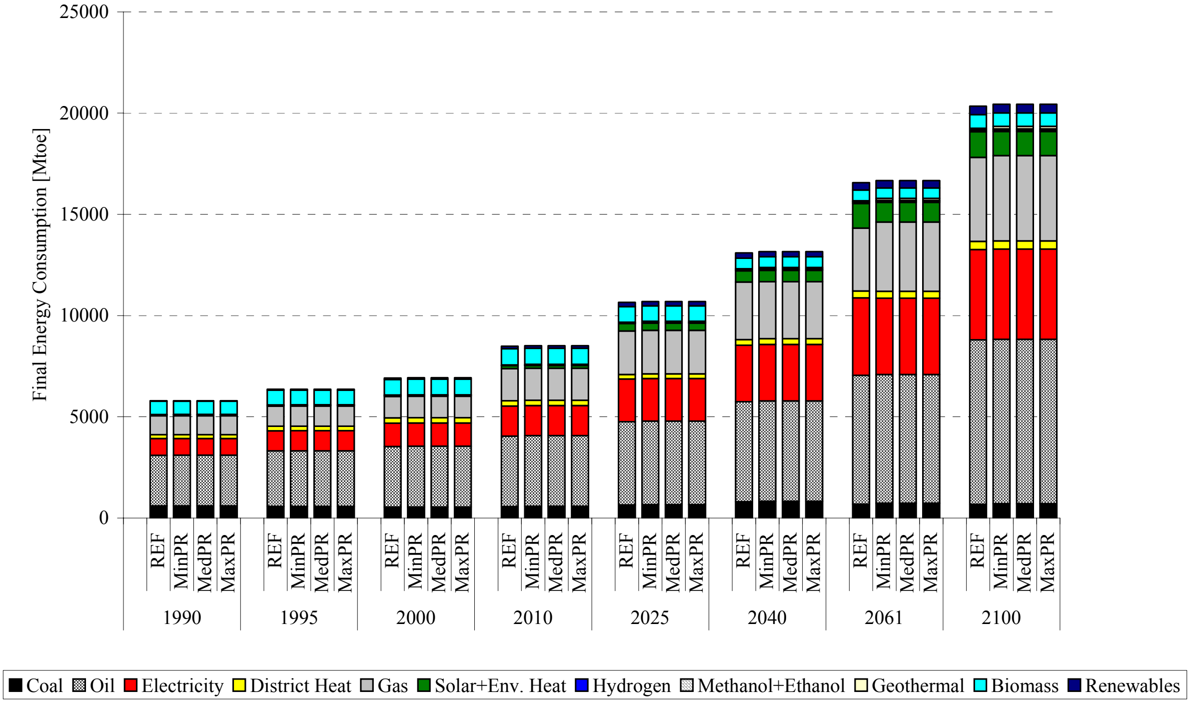

Figure 5-44: Final energy consumption comparison by scenarios

- **Electricity generation comparison by scenarios**

Electricity production from learning technologies in learning scenarios decreases as compared to base case. Electritity production from IGCC and CCGT technology decreases in learning scenarios compared to base case. The heat production from geothermal heat pump is higher in learning scenarios as compared to base case as this technology has not accounted knowledge gap. The cumulative electricity production form learning technologies and heat production from geothermal HP is provided in Table 5-7.

Table 5-7: Cumulative electricity and heat production from learning technologies

Cumulative electricity [TWh] and heat [PJ] production from learning technologies						
Scenario	Energy	Unit	MinPR	MedPR	MaxPR	Base
Coal	Electricity	[TWh]	43680	43680	43680	43680
Gas	Electricity	[TWh]	44729	44729	44729	44751
Solar	Electricity	[TWh]	958	958	958	958
Wind	Electricity	[TWh]	3601	3601	3601	3601
Geothermal	Heat	[PJ]	3148	3148	3130	2085

The generation of electricity decreases marginally in learning scenarios compared to base case for the higher specific cost originated due to knowledge lack for learning technologies in case of developing regions; that increase the overall system cost, for which the electricity production decreases.

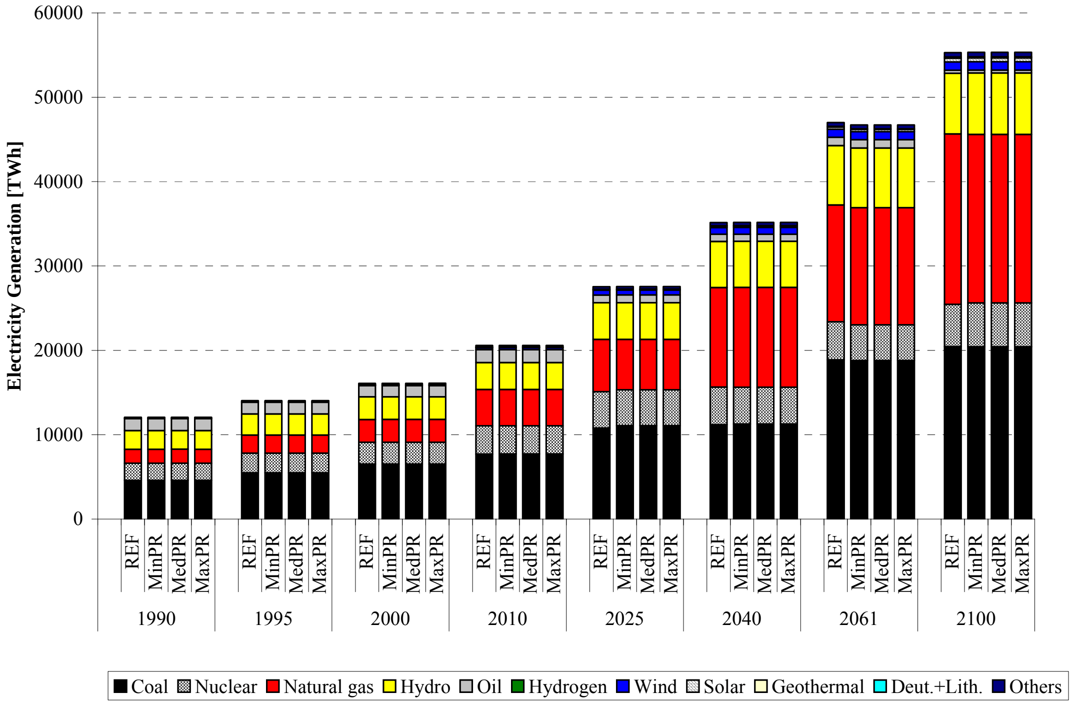

Figure 5-45: Electricity generation comparison by scenarios

- **Primary energy consumption comparison by scenarios**

The primary energy consumption increases in learning scenarios compared to the base case and the demand of energy carriers by period and by scenarios is provided in the Figure 5-46. The variation of total primary energy consumption in comparison to learning scenarios is very less but with respect to base case the variation is high. Solar and environmental heat energy differs a big margin in learning scenarios compared to the base case. This is due to the modeling of the knowledge gap in developing regions in terms of learning technologies having input as environmental heat that does not cost any thing inside the model. Therefore the environmental heat increases to a big margin in learning scenarios compared to base case. The difference of the primary energy demand between the learning scenarios and the base case comes around 2100 Mtoe towards the end period of the model horizon.

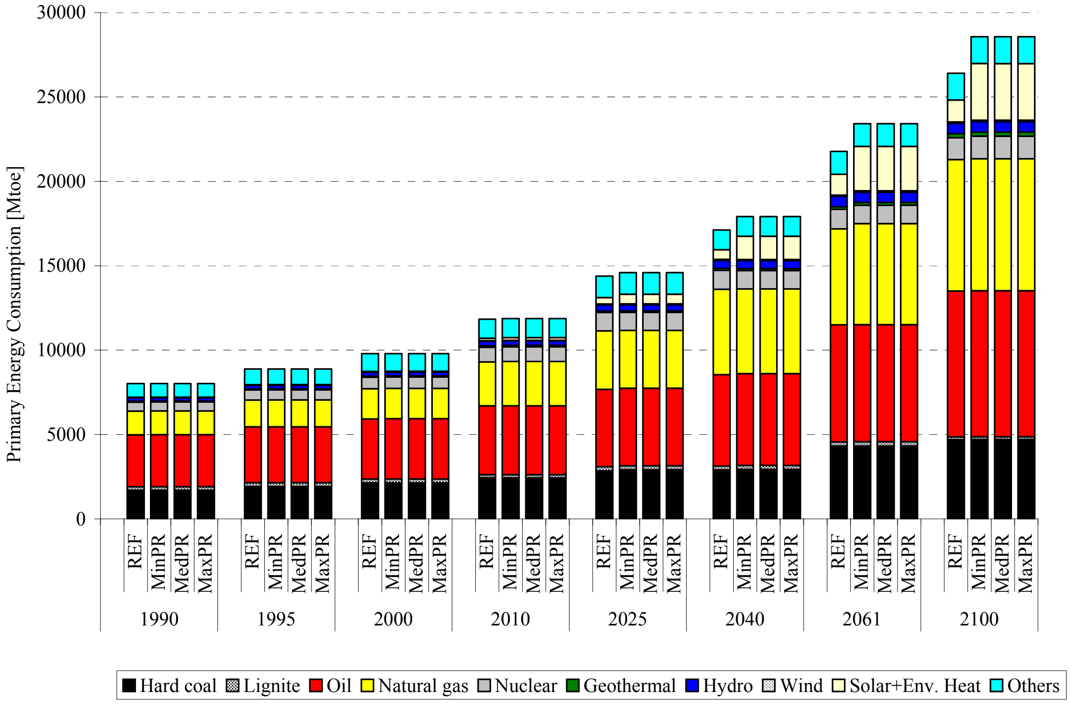

Figure 5-46: Primary energy comparison by scenarios

- **CO_2 emission comparison by scenarios**

The emission of CO_2 in the reference case is lower in some periods compared to learning scenarios. The increase in CO_2 emission in the learning scenarios is higher, due to more inefficient fossil fuel technology selection in leaning scenarios compared to the base case. The selection of polluting and inefficient technologies in learning is the cause of more carbon dioxide emission. Use of more coal, lignite and natural gas in the learning scenarios increase the CO_2 emission.

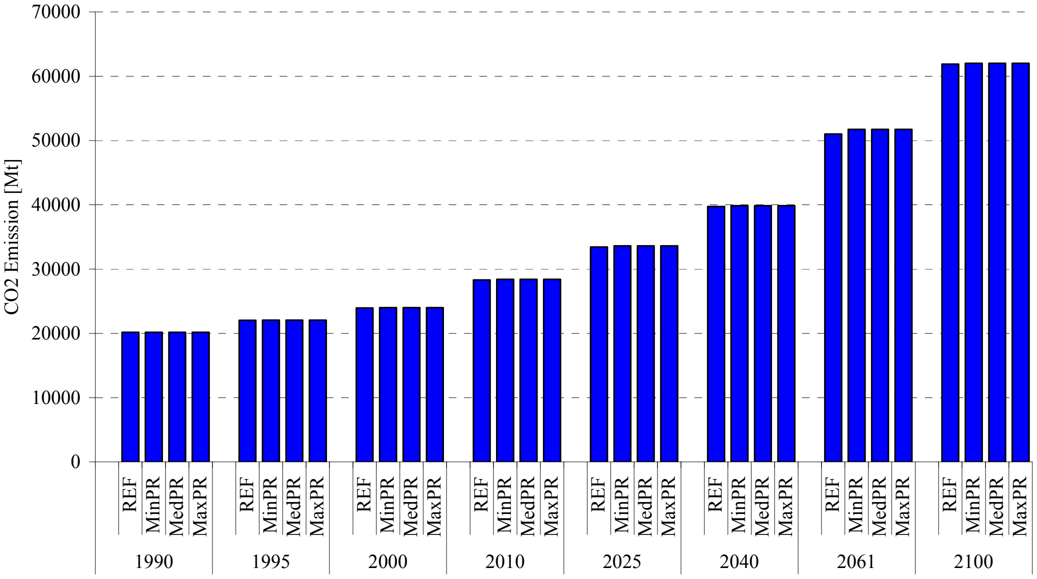

Figure 5-47: CO_2 emission comparison by scenarios

5.2.2.3 Comparison between the knowledge gap and time lag approaches

- **Comparison of the objective values**

The objective value of the knowledge gap and time lag approaches for medium progress ratio are different. Objective value is maximum for time lag approach and minimum for knowledge gap approach. The value of the objective in time lag approach is 214012.4 B€(00) and in knowledge gap approach is 213991.7 B€(00) for the model run till 2025, i.e., only for 8 periods starting from 1990 to 2025. The difference of the objective value is around 0.00967%, which is very small. The increase in objective value is due to learning investment incurred for the minimum capacity development of the learning technologies to fulfil minimum renewable electricity production and lapse of discount factor for developing regions to use the learning technologies.

The lapse of discount factor arises for the developing regions those use the learning technologies one period after of the production of the learning technologies in the manufacturing region in time lag concept. In this case, already the manufacturing region invests in period ‘t’ for the learning technologies to be utilised in developing regions in the priod ‘(t+1)’. So the objective value sees the discounted investment cost for learning technologies of developing regions as $(1+r)^t$ than the value $(1+r)^{t+1}$. Thus the lapse of the discount factor comes for one period, which increases the objective value.

- **Comparison of specific cost development**

The specific cost of any technology in knowledge lack approach remains always in higher side or same with the specific cost development of the learning technologies in the time lag approach. Again the specific cost of the learning technologies in knowledge gap approach is different across the regions categorized as developed and developing. The specific cost development of the learning technologies with respect to time lag and knowledge gap approaches are presented in the Figure 5-48 and the development of the learning technologies subject to knowledge gap across regions are provided in Figure 5-49. IGCC technology reaches to floor cost 890 €(00)/kW in year 2020 in time lag approach, whereas in the case of knowledge gap approach the technology does not attain the floor cost till 2025 for developed regions and the specific cost of the technology is higher for the developing regions. In time lag approach, the early production of the technology to be utilised on later part of the time period reduces the specific cost of the technology early.

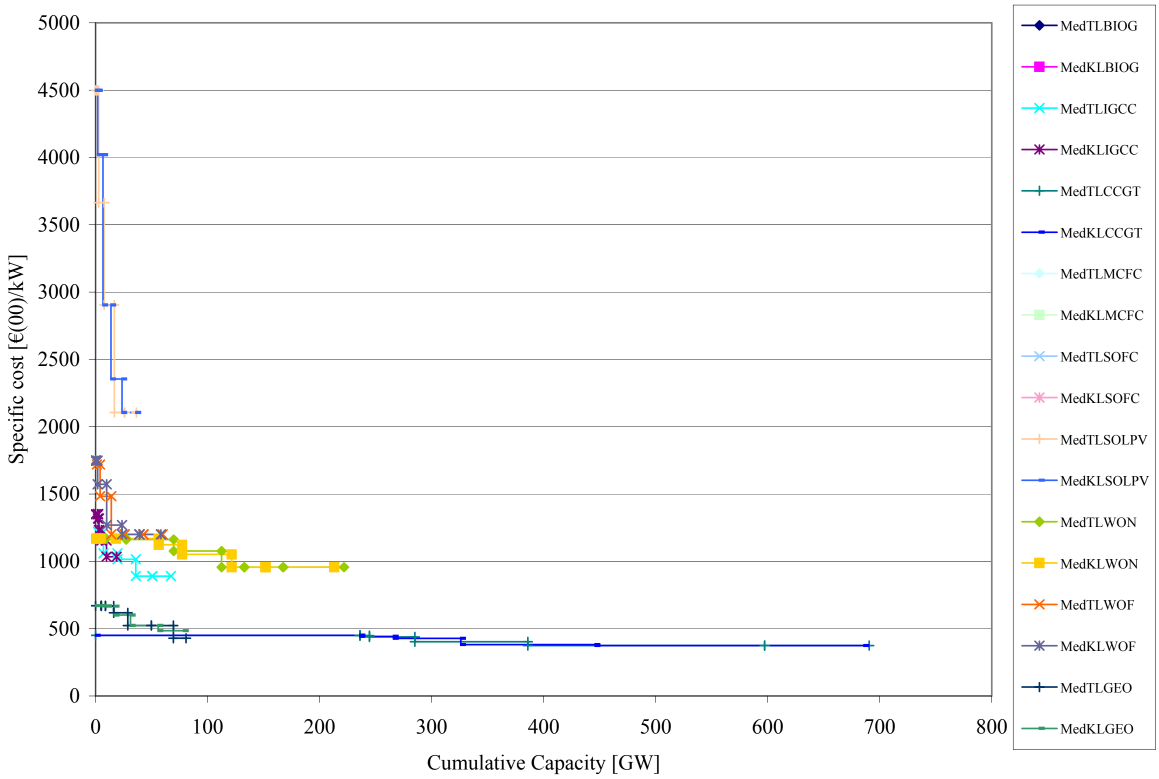

Figure 5-48: Specific cost development of learning technologies for world

Different specific cost of learning technologies is observed across developed and developing regions. For example developing regions see specific cost of the solar PV technology in year 1990 as 4500 €(00)/kW and in the same time developing regions attend the specific cost as 5190 €(00)/kW. For the same solar PV technology, developed regions visualise the specific cost as 2106 €(00)/kW in the year 2100 and developing regions see

2552 €(00)/kW in the endogenous learning of knowledge gap approach. Likewise for other learning technologies both developed and developing regions see different specific cost (see Figure 5-48).

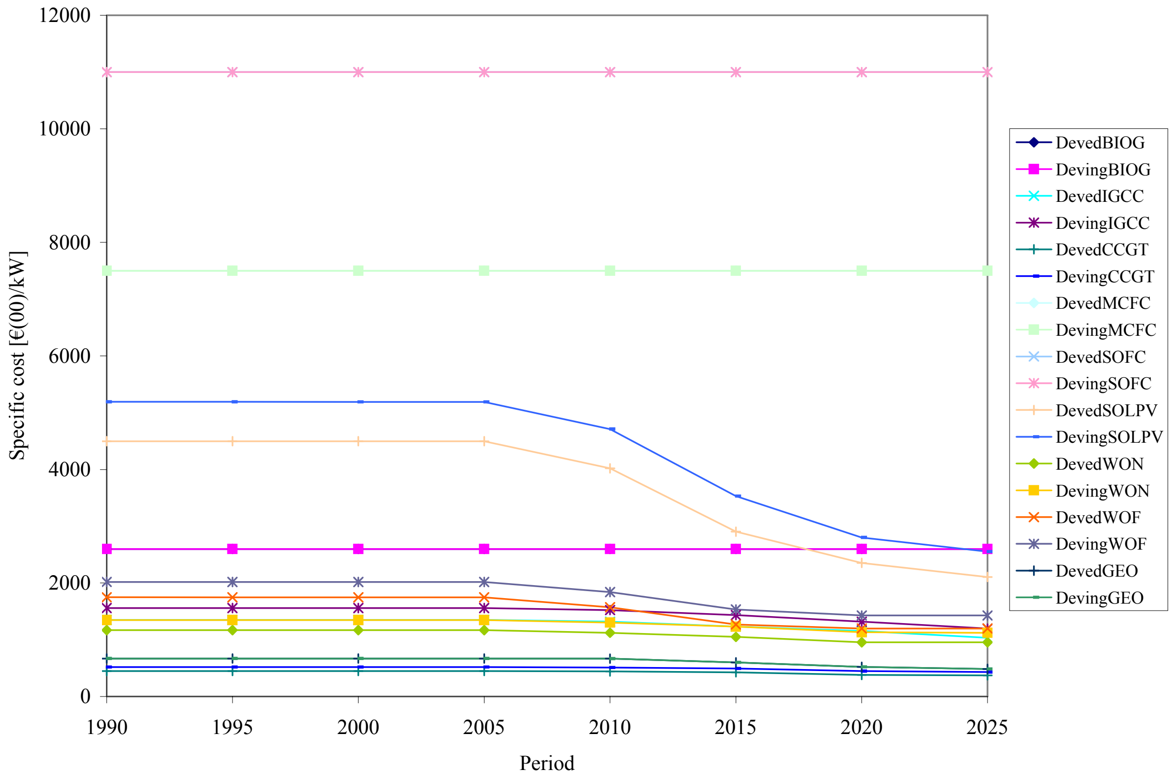

Figure 5-49: Specific cost development of learning technologies across regions
(Note: Deving stands for developing and Deved stands for developed regions)

- **Comparison by cumulative capacity development**

The learning technology diffusion takes place more inside the time lag approach, which reflects that early reduction of specific cost of the learning technologies in time lag approach, have advantage over the knowledge gap approach on technology diffusion. In this time lag approach developed regions use more learning technologies for the early reduction of the investment cost of learning technologies. IGCC and wind onshore enter to a small margin in time lag approach compared to the knowledge gap approach. Combined cycle gas turbine, wind offshore and geothermal heat pump penetrates more in time lag approach than knowledge gap approach.

Table 5-8: Cumulative capacity development of the learning technologies

Technology	Global Values	
	MedPRTL	MedPRKL
Integrated gasification CC	67.27	18.72
Combined cycle GT	690.60	686.00
Solar PV	36.40	36.03
Wind on-shore	221.81	213.11
Wind off-shore	59.86	58.28
Geothermal HP	80.69	78.55

(Note: MedPRTL stands for medium progress ratio with time lag concept and MedPRKL stands for the medium progress ratio with knowledge gap concept).

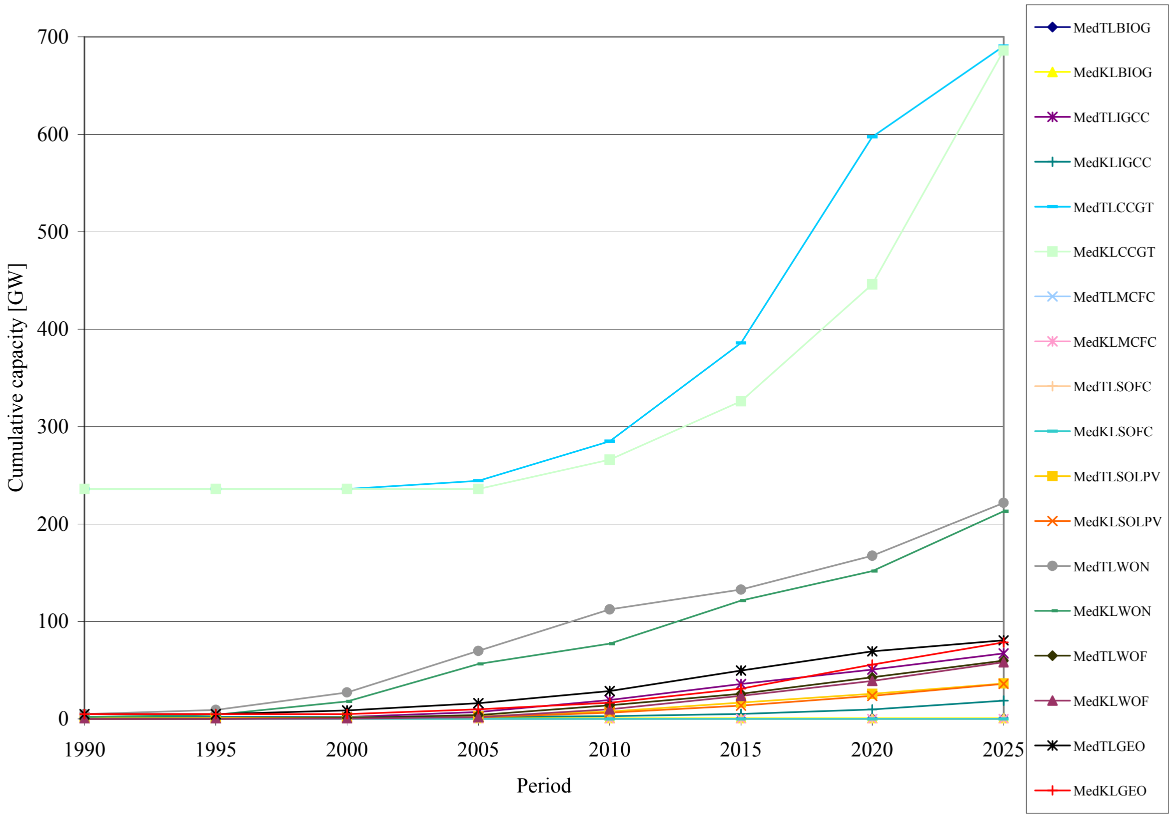

Figure 5-50: Cumulative capacity of global learning technologies by scenarios

The cumulative capacity development in knowledge gap and time lag approaches are different in manufacturing region. It is always in higher side for the time lag approach compared to knowledge gap approach. For some technologies the cumulative capacity development remains approximately same in both the approaches. The development of the cumulative capacity in manufacturing region by period is provided in the Figure 5-50. In time lag approach more IGCC is integrated in developed regions for the early reduction of the investment cost. Combined cycle gas turbine and geothermal HP increase in EU25 and R_OECD regions in time lag approach and wind onshore increases in EU25 and R_OECD regions. In time lag approach the developed regions benefited by the early reduction of the investment cost contributed by developing regions.

5.2.2.4 Summary and conclusion of learning concept

Global learning without knowledge gap and time lag has advantage compared to regional learning and promotes more utilization of the CCGT, wind onshore and geothermal HP inside the energy system of developed and developing regions subject to uncertainty in learning rates. In global learning all regions integrate more CCGT and geothermal HP but EU25 and R_OECD integrate more wind onshore in learning scenarios compared to base case as the advantage of high load factor of wind onshore is realized in these regions. IGCC technology penetrates to its maximum value in all scenarios. R_OECD, India and China integrate more IGCC technology in learning scenarios compared to base case as they have high coal resources and take advantage of investment cost reduction jointly.

Low progress ratio drags the technology to reach the floor cost quickly by small amount of capacity installation, i.e., reaching less cumulative capacity. This induces the heavy installation of the learning technologies in regional energy system, as the learning investment required is less. In case of lower learning rates, the specific cost reduction is in slow process. Thus the selection of the learning technologies is less compared to other sets of progress ratios. In the global learning scenarios, it is observed that the penetration of learning tehnologies generally higher for low progress ratio and decrease as the progress ratio increases. The production of electricity from learning technologies increase in learning scenarios compared to base case. Total final energy consumption, primary energy consumption and overall CO_2 emission increase in global learning without knowledge gap and time lag approach.

In case of global learning with knowledge gap concept, CCGT technology penetrates less in learning scenarios than the base case due to higher cost part in the developing regions originated from the knowledge lack point. In this case developed regions use more CCGT technology and developing regions use less compared to the base case. Wind onshore, wind offshore and solar PV penetrates equally in all scenarios as they are meant to fulfil the minimum renewable electricity out of them. Utilisation of IGCC technology decreases in developing regions and increase in developed regions. The production of electricity decreases in learning scenarios for the higher cost imposed by knowledge lack part. Final energy consumption, primary energy consumption and overall CO_2 emission increases in learning scenarios with knowledge gap compared to base case.

Though the knowledge gap and time lag reflects the reality of technological knowledge and technology transfer, still its presentation retards the global learning. Therefore other technologies inside the model compete even with promising learning technologies to occupy their place. The comparison of global learning with knowledge gap and global learning with time lag concepts on medium progress ratio has been carried out, in which the learning technology diffusion is more in time lag concept than knowledge lack. IGCC, CCGT, wind onshore and geothermal heat pump penetrates more in global energy system on time lag concept than knowledge lack. Early investment on new capacity development for developing regions by manufacturing region reduces the investment cost of learning technologies early, which provides incentive to the developed regions to use more the learning technologies available.

In learning theory, the learning investment and specific cost are major deciding factors behind the technology selection. Technologies like bio-gasification, solid oxide fuel cell and molten carbonate fuel cell do not enter in base case and in any other learning scenarios. The specific cost is so high that the model does not select this technology for energy production and in case of learning, it requires too high learning investment that model does not want to invest that much, rather to investment in other technologies.

The floor cost approach, that represents more towards the true specific cost development of the technology inside optimization subroutine, affects the model solution. Selection of the floor cost has significant influence on the technology selection. The lower value of the floor cost of a technology promotes more learning technologies by the model than the higher value of the floor cost of the same technology. The electricity production from learning technologies increases in global learning without knowledge gap and time lag concept but in global learning with knowledge gap concept it decreases.

6 Conclusion and Recommendations

6.1 Conclusion

The study focuses on the fulfilment of global energy demands subject to regional reserves and resources. In addition, it emphasises global learning both with and without knowledge gap and time lag concepts. The study investigates the transition of technology mix, fuel mix and their interplay inside the energy system up to the year 2100. Data were collected from various sources and put in the TIMES G5 model for five regions of the globe.

The analytical approach for the specific cost reduction of a nascent technology is based on the learning theory approach in which the specific investment cost reduces with respect to knowledge accumulation by development and deployment of the technology cumulative capacity and R&D expenditure. Due to the knowledge gap between the developed and developing regions, the penetration of the technologies decreases inside the global market. How especially climate compatible and cutting edge technologies can penetrate into regional energy systems to solve the problems of energy security and environmental pollution (global) through eco-efficiency subject to global learning with knowledge gap and time lag approaches.

The merit of this work is that it includes the global learning phenomenon with technology gap concepts by a mixed integer programming approach, in a five-regional bottom-up global energy system model developed on *T*he *I*ntegrated *M*ARKAL *E*FOM *S*ystem (TIMES) framework, to realise the future road map of learning technologies for the fulfilment of the energy demand on a long-term basis. Also how the diffusion of the technologies into regional energy systems in technology gap approaches provides the co-benefit to the developed and developing regions in different forms is presented inside this work. Also the work studies different climate stabilisation scenarios to understand the reduction potential of CO_2 that lies inside various sectors of different regions, as well as the behaviour of fuel switching and technology penetration over time subject to the level of stabilisation.

In total final energy consumption of the reference scenario, the industry sector holds the highest share in the initial periods of the model horizon, followed by residential, transport, commerce and non-energy use sectors. Towards the end periods, the transport sector secures first position followed by industry, residence, commerce and non-energy use sectors. In the industry and commerce sectors, all energy carriers increase their share in total, except coal and oil. Gradual shifting of the conventional energy carriers and penetration of commercial energy carriers takes place in all sectors of the regional energy system of all regions. Gas and electricity increase their shares. Heat pumps are used more for cooling and heating. Gas, solar and geothermal heat pumps enter inside the base case in commerce, residence and industry sectors. The share of natural gas, LPG and electricity in the household sector remains high compared to other fuels. Solar energy is used to a significant amount for heating, cooling and cooking demands. Oil remains as the dominant fuel carrier in the transport sector throughout the model horizon. Bio-fuels, H_2 and synthetic fuels participate marginally in the energy demand of the transport sector. Gradual shifting from coal to diesel and electric locomotives increases the demand for oil and electricity in the transport sector. Ethanol, electricity, RME and kerosene boost their shares from the starting to end periods of the model horizon. Shares of LPG and CNG are reduced over time in the developed regions but increase in the developing regions.

Substantial changes in the electricity production system and rapid fuel switching occur inside the model. The future global electricity system plausibly relies to a certain extent on coal-based power generation. Coal remains an important source to meet the fast growing electricity demand in developing regions. More efficient clean coal technologies gain sizeable market shares in generation and conventional coal-fired power plants will phase-out at the end of the time horizon. The share of coal in electricity production decreases towards the end periods compared to initial periods of the model horizon in all regions because of the integration of renewable, low emission and non-emitting fuels. Coal technologies are "locked-in" to a big margin especially in India and China as the coal reserves and resources are high and economically exploitable in these regions. These two regions use around 50% of the world coal consumption in the future in order to satisfy the heavy growth of their electricity demand. Nevertheless, the position of coal in the electricity production mix changes substantially over the time horizon, making IGCC, Coal Fluidised Bed Combustion (CFBC), and advanced coal power plants as major market players. Natural gas is also a desirable option for electricity production in many parts of the world on account of its relatively higher efficiency and low carbon content. It is a more attractive option for GHG mitigation and climate stabilisation than coal. Gas based technology such as Combined Cycle Gas Turbine (CCGT) outperforms other technologies in all regions in future periods. Gas combined cycle experiences a vigorous growth, whereas co-generation becomes an attractive option for the regions having more district heat demand, especially regions with a cold climate. Nuclear energy consumption increases in the future. Generally the nuclear power production declines in the EU25 and R_OECD regions marginally for the nuclear phaseout policy of developed regions, whereas it increases due to heavy installation in developing countries like India, China, South Korea and North Korea of R_NOECD region /WEO 2004/. The electricity production from nuclear sources increases by three times from the starting to the end period of the model horizon.

Among the renewable energies represented in the TIMES G5 model, wind, small hydro, biomass, solar, waste and geothermal energies play an important role. All the renewable technologies enter inside the base case for the satisfaction of minimum renewable electricity production criteria. At the present state of development emerging low or non-emission technologies, e.g., fuel cells, fusion and bio-gasification technologies are expensive in comparison to conventional fossil-based technologies; therefore the model does not invest in these technologies.

In primary energy demand projections, the future availability and prices of natural resources are crucial variables in the long-range projections of the world energy development. Thus the findings and conclusions of five regional global model studies are significantly influenced by implementation of their finite resource stock, which shows that depletion raises the prices and slows production. The shares of fossil fuels remain high in supplying the energy in the global energy context, where oil is the dominant energy source, whose market share declines marginally from the starting to the end period of the model horizon. In the refinery sector, all regions increase their capacity except the EU25 region in future years because of the approximately stabilised mobility demand and the increased market share of alternative fuels. The major energy carriers traded between the regions are crude oil, natural gas, hard coal, electricity and petroleum products. One important result of this study is that the reserves and resources on a regional basis are sufficient to fulfil the demands of the whole world. The assumed potentials in reserves and resources are the highest from the projections of all sources and include the conventional and non-conventional resources for certain types of energy carriers like oil and natural gas. The highest projection of the reserves and resources is given by /SAUNER 2000/. It incites that maybe future technologies will improve enough to identify more economically recoverable resources. Perhaps the unconventional resources peered today can be converted into conventional resources through technological development and competitive leap-frogging of the fuel prices. The regions that feel a deficiency in crude oil and natural gas are EU25, INDIA and CHINA. The other two regions R_OECD and R_NOECD have enough resources and reserves to fulfil their demands. They can export the energy carriers that are needed by EU25, INDIA and CHINA especially crude oil and natural gas.

The total CO_2 emission increases three-fold within the modelling horizon considered from the year 1990 to the year 2100. The power generation sector is the largest CO_2 emitter followed by the transport, industry, commerce and residence, non-energy use, refinery and other sectors. CO_2 emission is increased considerably in the power generation sector due to more coal consumption in developing regions. Total CO_2 emission inside this study from 1990 to 2100 refers to 590-ppmv (1265 GtC in the upper atmosphere) carbon concentration stabilisation in the atmosphere. In the climate stabilisation scenarios the production of electricity increases, total final energy demand decreases, and so does the sectoral energy demand. Inside the sectoral energy demand, fossil fuel integration decreases and the integration of non-CO_2 producing energy carriers increase. Fuel cells diffuse into the sectoral energy demand and hydrogen penetrates heavily to fulfil the mobility demand in the transport sector towards the end periods of the model horizon. Initiation of the fuel switching starts from 2005 onwards in stabilisation scenarios. Major energy structure changes occur in the transport, industry and residence sectors of all regions. Electricity production switches from the emitting fossil fuels to CO_2 free energy carriers. IGCC with CO_2 sequestration, CCGT with CO_2 sequestration and hydrogen production from natural gas with CO_2 sequestration facility technologies are selected from 2055 onwards in the climate stabilisation scenarios. Fusion technology disseminates towards the end periods of the model horizon. Nuclear, hydro and renewable technologies enter heavily for the electricity production. Capacity installation for electricity generation increases highly as the overall utilisation factor decreases. CO_2 emission is reduced by sectors, by regions and by fuels. The temperature of the atmosphere rises by a maximum of 2.41°C and deep ocean layers by a maximum of 0.33°C till the year 2100.

Global learning subject to knowledge gap and time lag is tested inside the TIMES G5 model developed on *T*he *I*ntegrated *M*ARKAL *E*FOM *S*ystem (TIMES) framework, to realise the future road map of learning technologies for the fulfilment of the energy demand on a long-term basis. Nevertheless, the technological progress and transition to sustainable energy-supply patterns is autonomous than occurring by interaction between socio-economic parameters inside the energy system. In case of the global learning subject to the technology gap in the term of knowledge gap and time lag concepts, the total system cost increases and also the cost of energy production. The reverse phenomenon is observed in the global learning scenarios without the knowledge gap and time lag concepts. Learning technologies penetrate more inside the regional energy systems of all regions in the global learning without knowledge gap and time lag concepts than base case; and also in the case of global learning with knowledge gap and time lag concepts. To reduce the cost and increase in the penetration of the new technologies inside the regional energy production of global energy system need the “win-win” strategy.

The investment cost of learning technologies without knowledge gap and time lag concepts decreases more by the combined effort of five regions in the development of cumulative capacity, therefore the selection of the learning technologies increases in each region. The market penetration of CCGT, wind onshore and geothermal HP is sensitive to the choice of technology-specific learning rates. Nonetheless, the variations in market share reported for robust technologies (e.g., CCGT) are less sensitive to the modification of LR than marginally used technologies. The low progress ratio makes the technology to reach the floor cost quickly with a small amount of the cumulative capacity installation. This induces more installation of the learning technologies, as the learning investment required is less.

IGCC technology is integrated more inside the R_OECD, R_NOECD, India and China energy systems. Especially the regions India and China get advantage on specific cost reduction in global learning on IGCC technology. Similarly, CCGT is integrated more in R_OECD, EU25 and R_NOECD regions. Geothermal heat pump technology penetrates in EU25, R_OECD, R_NOECD and China’s energy systems more. Wind onshore penetrates into the EU25 and R_OECD regions more in global learning without knowledge gap and time lag concepts for the higher load factor of the technology in these regions compared to others. Different regions integrate the learning technologies differently subject to uncertainties in learning rates. Learning technology integration inside the regional infrastructure increases in global learning without technology gap and time lag concepts for low PR. The integration of learning technologies decreases with the increase in PRs (1-LR) that reflects the influence of uncertainty in learning rates for diffusion of the technologies across the regions. The electricity production based on learning technologies increases in global learning without knowledge gap and time lag approaches but decreases in the global learning scenarios with knowledge gap concept. After all, the intelligent integration of learning technologies in the future energy system will be the challenge forever.

6.2 Recommendations for further research

The work discovered and exposed to many further research areas during this work. The first group proposes the directions for enhancement of the modeling framework. The second group addresses issues that could extend the scope and profoundness of impact assessment of theories and scenarios in general and the case of learning in particular.

From the modelling framework, detailed modelling of the industrial sector requires considerable attention and system analysis. Modelling of other emission factors than CO_2 could be inserted and analysed inside the model. Different policies can be formulated on the basis of regions inside the multi regional global energy model. The policies and their impacts on regional energy systems have considerable effect on the global energy system such as climatic condition by increase in atmospheric carbon concentration and stabilisation by the integration of global electricity network. Apart from this, there are many regional policies based on the phase-out of fossil fuels, introduction of biomass and renewable technologies, heavy installation and phase-out of nuclear, reduction of local and global pollution and phase-in of the clean and less polluting energy carriers. Further work is required on the dis-aggregation of combined diversified regions, for detailed projection and prediction of the energy requirement; energy situation and energy trading, local and global emissions; and emitted pollution level. The sensitivity analysis can be handled on change in GDP, population, person- and ton-kilometre demand; general and technology specific discount rates and future investments, impact analysis of international trade on CO_2 and green certificates; GHG mitigation policies, renewable policies, local pollution constriction and external cost on energy pollution can be tested by formulation of different scenarios. Saving measures can be analysed for different sectoral heat and electricity demand.

The action should be initiated from the present time for the future sustainability of the climate on the viewpoint of technology diffusion. So the degradation and deterioration of the climate from both a local and global point of view may be averted. Leaving the action until to the last minutes will have serious effects on to the energy system and climate; and requires more dramatic, expensive and disruptive changes later. Therefore, early and well-planned action is required to frame the environmental problems, which may simulate advanced, nascent, non-exhaustible and renewable technologies inside the regional energy system.

The learning theory can be addressed to end use technologies those utilise in end use sectors; and simultaneously have a high learning potential. As well, it can be applied to the technologies used in alternative fuels production, transport vehicles, refineries, CCS (Carbon Capture and Storage), extraction and exploration. Co-operation among industrialised regions and developing regions in research, development, demonstration and deployment (RD3) of more efficient and cleaner energy technologies may foster international learning processes that will contribute to boost their competitiveness in the global energy markets, thus accelerating their penetration and offering long-term environmental and economic benefits /Barreto 2001/. Many learning methodologies were developed during this work was conducted. Those methodologies can be inserted and tested inside the energy optimisation model for the validation. The methodologies are introduction of subsidy in learning theory for individual learning technology; global learning with a discontinuity in the time lag in-between developed and developing regions to understand the behaviour of the learning technologies penetration across the regions; sudden freezing of the knowledge gap after a certain time period across the developed and developing regions; the continuous decrease of knowledge gap to attain zero value between developed and developing regions; and concepts on two factor learning curve. Endogenous floor cost can be implemented rather than exogenous calculation and implementation.

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Annex A

Countries inside each region of TIMES G5 model:

EU25 (Austria, Belgium, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxemburg, Malta, the Netherlands, Poland, Portugal, the Slovak Republic, Slovenia, Spain, Sweden and the United Kingdom).

R_OCED (USA, Mexico, Canada, Australia, South Korea, Japan, New zealand, Iceland, Norway, Switzerland, Turkey).

India (India)

China (China)

R_NOECD (rest countries of world).

Table A-1: Technology specification for bio-fuel, H_2 and synthetic fuel production

Technologies for biogas and bio-fuel production					
Technology	Abbrev.	Inv. Cost	Fixed O&M	Var. O&M	Efficiency
		[€(00)/Gj/a]	[€(00)/Gj/a]	[€(00)/Gja]	[Fraction]
Biomass conversion	WOBIOE1	15.85	3.96	0.00	0.90
Biogas production	WOBIOE3	44.39	2.06	0.00	0.70
Technologies for synthetic fuel production					
Technology	Abbrev.	Inv. Cost	Fixed O&M	Var. O&M	Efficiency
		[€(00)/Gj/a]	[€(00)/Gj/a]	[€(00)/Gja]	[Fraction]
Coal gasification	WOCOLE1	28.53	1.40	0.22	0.95
Coal gasification with CO2 seq.	WOCOLE2	32.81	1.46	0.25	0.90
Natural gas conversion	WOGASE1	11.35	0.38	1.11	0.49
Natural gas conversion with CO2 seq.	WOGASE2	24.04	0.57	1.11	0.42
Technologies for hydrogen fuel production					
Technology	Abbrev.	Inv. Cost	Fixed O&M	Var. O&M	Efficiency
		[€(00)/Gj/a]	[€(00)/Gj/a]	[€(00)/Gja]	[Fraction]
Bio-gasification	WOBIOE2	63.26	2.33	0.27	0.49
Coal partial oxidation	WOCOLE3	28.32	3.74	0.83	0.59
Coal partial oxidation with CO2 seq.	WOCOLE4	47.52	6.42	0.21	0.53
Gas steam reforming	WOGASE3	11.23	1.48	0.14	0.66
Gas steam reforming with CO2 seq.	WOGASE4	18.70	2.52	0.58	0.60

Table A-2: Power plant residual capacity of EU25

Power plant residual capacity of EU25 [GW									
Fuel	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Coal	172.32	171.59	170.87	153.79	104.10	64.37	35.33	14.59	6.32
Oil	99.64	81.07	70.50	57.75	36.72	21.69	12.95	3.23	0.00
Natural gas	93.11	92.94	92.76	88.41	77.41	63.54	51.63	35.22	0.88
Nuclear	122.08	121.99	121.40	120.61	119.91	113.46	95.68	51.16	9.28
Hydro	121.90	121.90	121.90	121.90	121.90	121.00	121.00	120.20	120.20
Wind	0.03	0.03	0.03	0.03	0.01	0.00	0.00	0.00	0.00
Solar PV	0.04	0.04	0.04	0.04	0.04	0.03	0.00	0.00	0.00
Geothermal	0.73	0.73	0.73	0.73	0.73	0.15	0.00	0.00	0.00
Others	5.86	5.86	5.86	5.79	5.77	5.08	2.81	0.86	0.00

Table A-3: Power plant residual capacity of R_OECD

Power plant residual capacity of R_OECD [GW									
Fuel	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Coal	352.02	330.74	296.47	238.55	130.81	128.24	98.10	58.86	12.47
Oil	133.63	78.84	46.09	24.84	15.28	9.00	2.00	0.00	0.00
Natural gas	153.08	132.26	108.86	78.71	57.35	31.89	18.56	1.56	0.00
Nuclear	149.37	143.46	133.05	125.84	103.89	84.82	36.37	17.98	1.33
Hydro	218.50	218.50	218.50	218.50	218.50	216.50	216.50	216.50	216.50
Wind	0.94	0.94	0.94	0.94	0.70	0.33	0.00	0.00	0.00
Solar PV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Geothermal	3.55	3.55	3.35	2.65	2.50	1.89	0.28	0.00	0.00
Others	16.49	15.49	14.50	12.38	10.34	8.91	0.76	0.00	0.00

Table A-4: Power plant residual capacity of R_NOECD

Power plant residual capacity of R_NOECD [GW									
Fuel	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Coal	184.68	174.61	162.55	143.59	89.29	58.91	29.63	12.89	9.19
Oil	143.97	123.66	71.83	30.02	18.56	6.00	1.59	0.00	0.00
Natural gas	186.12	162.22	109.21	92.90	59.77	26.49	14.94	5.14	0.00
Nuclear	42.58	42.58	41.60	41.40	39.20	38.90	38.60	36.78	35.52
Hydro	199.09	199.09	199.09	198.75	198.75	196.00	194.58	183.40	171.23
Wind	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solar PV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Geothermal	5.07	4.97	4.87	3.80	2.55	1.57	0.25	0.00	0.00
Others	4.83	4.23	3.93	3.52	3.23	3.10	2.34	1.26	0.00

Table A-5: Power plant residual capacity of India

Power plant residual capacity of India [GW									
Fuel	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Coal	45.72	45.72	43.83	42.83	37.65	30.93	19.30	2.71	2.71
Oil	2.31	2.31	2.12	0.38	0.18	0.00	0.00	0.00	0.00
Natural gas	2.17	2.17	2.14	1.43	0.10	0.10	0.10	0.00	0.00
Nuclear	1.66	1.66	1.66	1.66	1.02	1.02	0.56	0.09	0.09
Hydro	18.40	18.40	17.55	17.55	16.65	15.00	13.50	10.87	7.02
Wind	0.53	0.53	0.47	0.19	0.03	0.03	0.03	0.00	0.00
Solar PV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Geothermal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Others	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table A-6: Power plant residual capacity of China

Power plant residual capacity of China [GW									
Fuel	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Coal	114.62	108.69	99.65	86.60	78.55	67.48	54.56	41.64	8.61
Oil	11.50	9.48	7.14	4.68	0.97	0.00	0.00	0.00	0.00
Natural gas	1.90	1.80	1.59	1.30	0.99	0.21	0.00	0.00	0.00
Nuclear	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydro	40.55	40.55	40.55	40.55	40.55	40.55	40.14	38.93	37.87
Wind	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solar PV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Geothermal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Others	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.00	0.00

Table A-7: Minimum renewable electricity production in EU25 [PJ]

Year	Biomass	Biogas	Waste	Small hydro	Wind onshore	Wind offshore	Geothermal	Solar PV
1990	26.21		4.96	84.64	9.16	0.00	6.68	0.01
1995	37.52		8.23	127.97	26.96	0.52	10.47	0.07
2000	50.30		11.81	164.76	47.00	3.43	14.24	0.22
2005	88.51	5.70	21.67	302.27	363.24	4.64	26.12	4.16
2010	149.10	8.51	31.25	420.66	373.45	69.39	37.95	12.50
2015	202.08	10.35	36.18	463.95	383.89	127.85	44.32	23.73
2020	273.60	12.40	41.24	497.89	393.71	214.13	51.10	40.20
2025	326.41	13.25	41.10	454.46	454.63	299.91	51.63	56.89
2030	413.96	14.78	42.50	414.78	599.58	431.21	54.41	82.13
2035	445.95	15.46	44.44	428.77	603.54	453.89	56.90	98.12
2040	480.59	16.20	46.57	444.14	608.16	479.02	59.62	115.65
2045	510.85	16.74	48.13	453.65	603.16	498.30	61.62	132.77
2050	541.33	17.28	49.69	463.07	596.79	517.81	63.62	151.00
2055	569.20	17.70	50.87	468.44	584.20	533.57	65.13	168.60
2061	601.80	18.14	52.17	473.28	566.27	551.65	66.78	190.02
2070	669.24	19.30	55.48	492.35	549.70	593.39	71.02	229.69
2080	757.41	20.84	59.91	518.35	530.80	649.17	76.70	281.03
2090	830.99	21.87	62.87	530.31	491.12	689.76	80.49	329.85
2100	861.78	21.73	62.46	512.96	422.44	694.01	79.96	362.09

Table A-8: Minimum renewable electricity production in R_OECD [PJ]

Year	Biomass	Biogas	Waste	Small hydro	Wind onshore	Wind offshore	Geothermal	Solar PV
1990								
1995								
2000								
2005	113.79	0.67	25.32	353.10	113.59	28.78	30.51	0.47
2010	141.73	0.88	30.52	410.85	172.34	67.77	37.07	23.53
2015	170.63	1.14	35.52	455.48	250.24	125.52	43.51	60.08
2020	194.24	1.40	38.62	466.28	340.61	200.53	47.86	109.85
2025	216.26	1.69	40.89	452.12	452.29	298.37	51.36	176.56
2030	235.18	2.00	41.47	404.66	584.95	420.69	53.09	261.23
2035	244.15	2.09	43.16	416.38	586.10	440.77	55.25	297.11
2040	254.87	2.19	45.25	431.49	590.84	465.37	57.93	337.93
2045	269.78	2.32	48.02	452.57	601.72	497.11	61.47	386.69
2050	276.39	2.39	49.45	460.82	593.88	515.28	63.31	427.37
2055	288.18	2.50	51.69	475.97	593.59	542.15	66.18	476.97
2061	300.18	2.61	54.08	490.64	587.04	571.89	69.23	536.88
2070	311.97	2.73	56.50	501.39	559.80	604.29	72.33	620.39
2080	317.35	2.80	57.88	500.78	512.80	627.16	74.10	703.21
2090	315.04	2.80	57.92	488.50	452.41	635.39	74.14	771.64
2100	313.17	2.80	57.98	476.20	392.16	644.27	74.23	840.35

Table A-9: Minimum renewable electricity production in R_NOECD [PJ]

Year	Biomass	Biogas	Waste	Small hydro	Wind onshore	Wind offshore	Geothermal	Solar PV
1990								
1995								
2000								
2005	83.12	4.68	9.36	163.72	11.21	0.00	0.00	4.68
2010	105.88	5.73	11.51	214.81	56.29	4.81	3.23	8.96
2015	122.18	6.41	12.82	255.96	290.04	11.38	7.56	14.05
2020	138.25	6.92	13.84	298.42	323.27	19.76	13.17	20.18
2025	153.44	7.40	14.71	342.08	353.85	29.99	20.02	27.42
2030	173.13	7.90	15.81	398.75	393.04	43.37	28.87	37.00
2035	186.86	8.02	16.17	444.73	417.25	57.63	38.42	46.69
2040	199.08	8.11	16.22	489.93	436.60	73.54	48.94	57.45
2045	211.91	8.00	16.14	539.74	455.82	91.92	61.23	69.67
2050	222.73	7.86	15.56	587.40	469.35	111.76	74.51	82.68
2055	237.64	7.58	15.16	648.47	488.90	135.97	90.64	98.92
2061	253.07	7.04	14.27	722.10	505.95	168.20	112.07	120.06
2070	256.16	5.49	11.19	781.70	486.48	208.75	139.17	145.68
2080	254.78	3.46	6.92	841.72	452.52	255.87	170.50	175.26
2090	247.71	1.13	2.25	889.65	405.04	302.49	201.73	203.99
2100	233.56	0.00	0.00	934.25	350.34	350.34	233.56	233.56

Table A-10: Minimum renewable electricity production in INDIA [PJ]

Year	Biomass	Biogas	Waste	Small hydro	Wind onshore	Wind offshore	Geothermal	Solar PV
1990								
1995								
2000								
2005	12.64	0.97	1.94	68.04	12.64	0.00	0.00	0.97
2010	18.32	1.28	2.54	90.19	18.68	1.41	0.00	1.98
2015	23.12	1.44	2.90	104.10	23.98	3.42	0.00	3.16
2020	27.77	1.57	3.13	114.37	29.26	5.89	0.00	4.51
2025	33.29	1.69	3.39	125.22	35.54	9.02	0.00	6.19
2030	38.62	1.77	3.51	132.70	41.75	12.57	0.00	8.05
2035	45.69	1.85	3.73	143.21	49.99	17.20	0.00	10.45
2040	53.48	1.93	3.87	152.70	59.13	22.63	0.00	13.26
2045	62.99	2.02	4.05	163.47	70.36	29.39	0.00	16.72
2050	74.08	2.10	4.16	174.29	83.52	37.55	0.00	20.86
2055	86.26	2.10	4.24	183.28	97.96	47.01	0.00	25.63
2061	104.24	2.13	4.26	195.18	119.56	61.23	0.00	32.77
2070	121.45	1.83	3.61	185.35	141.03	78.33	0.00	41.00
2080	138.43	1.29	2.59	163.74	162.76	97.27	0.00	49.96
2090	149.38	0.69	1.32	130.82	177.51	112.57	0.00	56.95
2100	158.38	0.00	0.00	95.03	190.06	126.70	0.00	63.35

Table A-11: Minimum renewable electricity production in CHINA [PJ]

Year	Biomass	Biogas	Waste	Small hydro	Wind onshore	Wind offshore	Geothermal	Solar PV
1990								
1995								
2000								
2005	45.91	2.42	4.83	144.98	6.87	0.00	1.21	2.42
2010	66.19	3.31	6.65	205.69	56.90	4.65	3.52	5.18
2015	79.28	3.80	7.59	242.40	67.47	11.22	6.40	8.32
2020	91.12	4.11	8.22	273.51	76.57	19.55	9.90	11.98
2025	102.37	4.38	8.71	301.77	85.06	29.57	14.05	16.25
2030	115.15	4.61	9.22	333.53	94.66	42.12	19.20	21.57
2035	123.45	4.58	9.22	350.45	100.22	54.72	24.27	26.63
2040	136.41	4.73	9.47	379.83	109.49	71.47	31.04	33.52
2045	143.38	4.53	9.15	390.57	113.45	86.82	37.10	39.49
2050	150.55	4.38	8.67	400.80	117.46	103.63	43.76	46.04
2055	157.63	4.08	8.16	410.17	121.35	122.09	51.03	53.25
2061	166.49	3.68	7.46	420.90	126.01	146.60	60.67	62.76
2070	175.10	2.88	5.88	421.68	128.74	182.79	74.78	76.49
2080	177.32	1.78	3.55	403.03	126.17	219.05	88.77	89.99
2090	180.46	0.58	1.16	383.84	123.63	258.94	104.18	104.76
2100	175.21	0.00	0.00	350.42	116.81	292.02	116.81	116.81

Table A-12: Bound on technology capacity and new capacities in EU25 [GW]

Technology lower bound [GW]		
	Hydro	Nuclear
Year	NCAP	CAP
1990		
1995		
2000		
2005	0.50	128.50
2010	1.93	123.80
2015	2.27	124.90
2020	2.62	125.10
2025	2.97	128.70
2030	3.31	128.60
2035	3.66	134.40
2040	3.56	141.00
2045	3.46	145.50
2050	3.36	145.50
2055	3.26	145.50
2061	3.19	145.50
2070	3.12	145.50
2080	13.99	145.50
2090	16.85	145.50
2100	24.70	145.50

Technology upper bound [GW]									
	Coal	Oil	Gas	Hydro	Nuclear	Biomass	Geothermal	Wind	Fusion
Year	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP
1990									
1995									
2000									
2005	10.00	15.00	340.00	22.00	35.00	7.00	7.00		
2010	10.00	15.00	340.00	22.00	35.00	8.00	7.00		
2015	10.00	15.00	340.00	22.00	35.00	9.00	7.00	45.00	
2020	10.00	15.00	340.00	22.00	35.00	10.00	7.00	45.00	
2025	10.00	15.00	340.00	22.00	35.00	11.00	7.00	45.00	180.00
2030	10.00	15.00	340.00	22.00	35.00	12.00	7.00	45.00	180.00
2035	10.00	15.00	340.00	22.00	35.00	13.00	7.00	45.00	180.00
2040	10.00	15.00	340.00	22.00	35.00	14.00	7.00	45.00	180.00
2045	10.00	15.00	340.00	22.00	35.00	14.00	7.00	45.00	180.00
2050	10.00	15.00	340.00	22.00	35.00	14.00	7.00	45.00	180.00
2055	10.00	15.00	340.00	22.00	35.00	14.00	7.00	45.00	180.00
2061	10.00	15.00	420.00	22.00	35.00	14.00	7.00	45.00	180.00
2070	15.00	19.00	420.00	35.00	55.00	14.00	13.00	80.00	280.00
2080	15.00	19.00	420.00	38.00	55.00	14.00	13.00	80.00	280.00
2090	22.00	19.00	420.00	39.00	55.00	14.00	13.00	80.00	280.00
2100	25.00	19.00	420.00	44.00	55.00	14.00	13.00	80.00	280.00

Table A-13: Bound on technology capacity and new capacities in R_OECD [GW]

Technology lower bound		
	Hydro	Nuclear
Year	NCAP	CAP
1990		
1995		
2000		
2005	3.50	180.27
2010	17.53	178.46
2015	15.89	178.78
2020	14.25	177.32
2025	12.61	182.75
2030	10.96	180.93
2035	9.32	183.73
2040	7.68	181.49
2045	7.21	182.24
2050	6.74	187.50
2055	6.26	180.00
2061	5.69	180.00
2070	26.84	180.00
2080	69.23	180.00
2090	73.61	180.00
2100	41.00	180.00

Technology upper bound [GW]									
	Coal	Oil	Gas	Hydro	Nuclear	Biomass	Geothermal	Wind	Fusion
Year	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP
1990									
1995									
2000									
2005	85.00	50.00	400.00	50.00	55.00		15.00		
2010	85.00	50.00	400.00	55.00	55.00		15.00		
2015	85.00	50.00	400.00	55.00	55.00	25.00	15.00	115.00	
2020	85.00	50.00	400.00	55.00	55.00	25.00	15.00	115.00	
2025	85.00	50.00	400.00	55.00	65.00	25.00	15.00	115.00	180.00
2030	85.00	50.00	400.00	55.00	55.00	25.00	15.00	115.00	180.00
2035	85.00	50.00	400.00	55.00	55.00	25.00	15.00	115.00	180.00
2040	85.00	50.00	400.00	55.00	55.00	25.00	15.00	115.00	180.00
2045	85.00	50.00	400.00	55.00	55.00	25.00	15.00	115.00	180.00
2050	85.00	50.00	400.00	55.00	55.00	25.00	15.00	115.00	180.00
2055	85.00	50.00	400.00	55.00	55.00	25.00	15.00	115.00	180.00
2061	135.00	50.00	500.00	55.00	55.00	25.00	15.00	115.00	180.00
2070	135.00	58.00	500.00	85.00	85.00	45.00	22.00	250.00	280.00
2080	135.00	58.00	500.00	102.00	85.00	45.00	22.00	250.00	280.00
2090	135.00	58.00	500.00	103.00	85.00	45.00	22.00	250.00	280.00
2100	135.00	58.00	500.00	105.00	85.00	45.00	22.00	250.00	280.00

Table A-14: Bound on technology capacity and new capacities in R_NOECD [GW]

Technology lower bound [GW]		
	Hydro	Nuclear
Year	NCAP	CAP
1990		
1995		
2000		
2005		45.40
2010		51.28
2015	20.0	61.67
2020	30.6	74.67
2025	41.2	88.75
2030	51.8	106.00
2035	62.4	91.60
2040	72.9	115.32
2045	83.5	137.65
2050	94.1	158.50
2055	104.7	179.36
2061	117.4	200.21
2070	119.5	241.00
2080	121.6	253.00
2090	123.8	273.00
2100	125.0	293.00

Technology upper bound [GW]									
	Coal	Oil	Gas	Hydro	Nuclear	Biomass	Geothermal	Wind	Fusion
Year	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP
1990									
1995									
2000									
2005						10.00	15.00		
2010						10.00	15.00		
2015	150.00		290.00	307.00	180.00	10.00	15.00	75.00	
2020	182.35	36.47	290.00	307.00	180.00	10.00	15.00	75.00	
2025	214.71	47.94	290.00	307.00	180.00	10.00	15.00	75.00	180.00
2030	247.06	59.41	290.00	307.00	180.00	10.00	15.00	75.00	180.00
2035	279.41	70.88	290.00	307.00	180.00	10.00	15.00	75.00	180.00
2040	311.76	82.35	290.00	307.00	180.00	10.00	15.00	75.00	180.00
2045	344.12	93.82	290.00	307.00	180.00	10.00	15.00	75.00	180.00
2050	376.47	105.29	290.00	307.00	180.00	10.00	15.00	75.00	180.00
2055	408.82	116.76	290.00	307.00	180.00	10.00	15.00	75.00	180.00
2061	447.65	130.53	450.00	307.00	180.00	10.00	15.00	75.00	180.00
2070	505.88	151.18	450.00	475.00	290.00	10.00	22.00	150.00	280.00
2080	570.59	174.12	450.00	475.00	290.00	10.00	22.00	150.00	280.00
2090	635.29	197.06	450.00	475.00	290.00	10.00	22.00	150.00	280.00
2100	700.00	220.00	450.00	475.00	290.00	10.00	22.00	150.00	280.00

Table A-15: Bound on technology capacity and new capacities in INDIA [GW]

Technology lower bound [GW]		
	Hydro	Nuclear
Year	NCAP	NCAP
1990		
1995		
2000		
2005	4.17	2.00
2010	6.63	2.47
2015	3.70	2.95
2020	3.54	3.42
2025	4.63	3.89
2030	5.73	4.37
2035	6.83	4.84
2040	7.92	5.32
2045	9.02	5.79
2050	10.12	6.26
2055	11.21	6.74
2061	12.53	7.65
2070	13.64	8.56
2080	14.76	9.24
2090	15.88	10.65
2100	17.00	11.00

Technology upper bound [GW]									
	Coal	Oil	Gas	Hydro	Nuclear	Biomass	Geothermal	Wind	Fusion
Year	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP
1990							0.00		
1995							0.00		
2000							0.00		
2005			5.00	10	10.00		0.00	5.00	
2010			10.00	20	10.00	8.00	0.00	10.00	
2015	40.00	5.00	15.00	30	10.00	8.00	0.00	15.00	
2020	44.71	5.00	20.00	40	10.00	8.00	0.00	20.00	
2025	49.41	5.00	25.00	50	10.00	8.00	0.00	25.00	30.00
2030	54.12	5.00	30.00	55	10.00	8.00	0.00	30.00	30.00
2035	58.82	5.00	35.00	60	10.00	8.00	0.00	35.00	30.00
2040	63.53	5.00	40.00	60	10.00	8.00	0.00	40.00	30.00
2045	68.24	5.00	45.00	60	10.00	8.00	0.00	45.00	30.00
2050	72.94	5.00	50.00	60	10.00	8.00	0.00	50.00	30.00
2055	77.65	5.00	55.00	60	10.00	8.00	0.00	60.00	30.00
2061	83.29	5.00	60.00	60	15.00	8.00	0.00	70.00	30.00
2070	91.76	5.00	80.00	60	15.00	8.00	0.00	80.00	75.00
2080	101.18	5.00	100.00	60	15.00	8.00	0.00	90.00	75.00
2090	110.59	5.00	100.00	60	15.00	8.00	0.00	90.00	75.00
2100	120.00	5.00	100.00	60	15.00	8.00	0.00	90.00	75.00

Table A-16: Bound on technology capacity and new capacities in CHINA [GW]

Technology lower bound [GW]		
	Hydro	Nuclear
Year	NCAP	NCAP
1990		
1995		
2000		
2005	19.05	5.30
2010	16.80	2.95
2015	12.90	3.40
2020	14.70	3.84
2025	16.50	4.29
2030	18.30	4.74
2035	20.10	5.19
2040	21.90	5.63
2045	23.70	6.08
2050	25.50	8.53
2055	27.30	11.98
2061	29.46	13.42
2070	32.70	16.19
2080	36.30	17.74
2090	39.90	19.63
2100	43.50	21.53

Technology upper bound [GW]									
	Coal	Oil	Gas	Hydro	Nuclear	Biomass	Geothermal	Wind	Fusion
Year	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP
1990									
1995									
2000									
2005		5.00	5.00				15.00	45.00	
2010	80.00	5.00	10.00			8.00	15.00	45.00	
2015	83.89	5.00	15.00	85.00		8.00	15.00	45.00	
2020	87.78	5.00	20.00	85.00	30.00	8.00	15.00	45.00	
2025	91.67	5.00	25.00	85.00	30.00	8.00	15.00	45.00	50.00
2030	95.56	5.00	30.00	85.00	30.00	8.00	15.00	45.00	50.00
2035	99.44	5.00	35.00	85.00	30.00	8.00	15.00	45.00	50.00
2040	103.33	5.00	40.00	85.00	30.00	8.00	15.00	45.00	50.00
2045	107.22	5.00	45.00	85.00	30.00	8.00	15.00	45.00	50.00
2050	111.11	5.00	50.00	85.00	30.00	8.00	15.00	45.00	50.00
2055	115.00	5.00	55.00	85.00	30.00	8.00	15.00	45.00	50.00
2061	119.67	4.00	60.00	85.00	30.00	8.00	15.00	45.00	50.00
2070	142.00	4.00	70.00	140.00	45.00	8.00	20.00	65.00	95.00
2080	148.08	4.00	80.00	143.00	65.00	8.00	20.00	65.00	95.00
2090	189.00	4.00	90.00	145.00	65.00	8.00	20.00	65.00	95.00
2100	191.00	4.00	100.00	148.00	65.00	8.00	20.00	65.00	95.00

Table A-17: Cumulative capacity of learning technologies developed across world

Cumulative capacity in different periods [GW]					
Technologies	1990	1995	2000	2005	Name of the Plants
WEBION3	0.0010	0.0010	0.0070	0.0070	Bio-gasification CHP plant
WECOLN3	0.3400	0.5900	2.0720	2.0720	IGCC plant
WEGASN3	46.6670	106.6600	236.0000	236.0000	Combined Cycle Gas Turbine (CCGT)
WEMCFCN		0.0001	0.0029	0.0146	Molten Carbonate Fuel Cell (MCFC)
WESOFCN		0.0001	0.0003	0.0023	Solid Oxide Fuel Cell (SOFC)
WESOLN2	0.0844	0.3400	1.1000	2.0100	Solar PV plant
WEWINN1	2.8900	4.7710	18.4140	38.1670	Wind Onshore plant
WEWINN2	0.0008	0.0108	0.0408	0.7008	Wind Offshore plant
WRGEOT	4.9540	8.6050	15.1450	15.1450	Geothermal Heat Pump (HP)

(Source: /Abbi 2003/, /Claeson 1999/, /forestry.biomass/, /Gasification-SFA/, /iga.geoworld/, /Junginger and Faaji/, /Martinus et al. 2005/, /volker.pv/, /volker.ren-leistung/, /Wene et al. 2000/)

Table A-18: Learning technology bound across the globe [GW]

Technology lower bound around world [GW]			
	IGCC	CCGT	Geothermal HP
Year	NCAP	NCAP	NCAP
1990			
1995			
2000			
2005			5.00
2010	0.27	9.00	6.58
2015	0.68	18.00	8.16
2020	1.35	36.00	9.74
2025	2.70	72.00	11.32
2030	10.80	135.00	12.89
2035	21.60	157.50	14.47
2040	43.20	180.00	16.05
2045	86.40	202.50	17.63
2050	165.00	225.00	19.21
2055	171.00	229.20	20.79
2061	178.20	234.00	22.68
2070	189.00	241.80	25.53
2080	201.00	250.20	28.68
2090	213.00	258.60	31.84
2100	225.00	267.00	35.00

Technology upper bound around world [GW]									
	IGCC	CCGT	Biogasification	Solar PV	Solid oxide fuel cell	Molten carbonate fuel cell	Wind onshore	Wind offshore	Geothermal HP
Year	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP	NCAP
1990	0.00	0.00	0.00	0.10	0.00	0.00	3.50	0.10	0.00
1995	0.00	0.00	0.00	0.30	0.00	0.00	4.80	0.30	0.00
2000	0.00	0.00	0.00	1.30	0.00	0.00	14.90	0.50	0.00
2005	0.00	0.00	0.00	2.60	2.00	2.00	42.00	2.90	50.00
2010	0.90	30.00	5.90	5.20	4.00	4.00	84.00	8.04	65.79
2015	2.25	60.00	8.35	10.40	8.00	8.00	168.00	16.00	81.58
2020	4.50	120.00	10.80	20.80	16.00	16.00	336.00	64.00	97.38
2025	9.00	240.00	13.25	41.60	32.00	32.00	672.00	256.00	113.16
2030	36.00	450.00	15.70	83.20	64.00	64.00	1344.00	1024.00	128.95
2035	72.00	525.00	18.15	166.40	128.00	128.00	2688.00	2048.00	144.74
2040	144.00	600.00	20.60	208.00	160.00	160.00	3360.00	2560.00	160.53
2045	288.00	675.00	23.05	228.80	176.00	176.00	3696.00	2816.00	176.32
2050	550.00	750.00	25.50	239.20	184.00	184.00	3864.00	2994.00	192.11
2055	570.00	764.00	27.95	244.40	188.00	188.00	3984.00	3083.00	207.90
2061	594.00	780.00	30.89	247.00	190.00	190.00	3990.00	3127.50	226.84
2070	630.00	806.00	35.30	248.95	191.50	191.50	4021.00	3160.88	255.26
2080	670.00	834.00	40.20	250.00	192.00	192.00	4030.00	3170.00	286.84
2090	710.00	862.00	45.10	250.00	192.00	192.00	4030.00	3170.00	318.42
2100	750.00	890.00	50.00	250.00	192.00	192.00	4030.00	3170.00	350.00

Curriculum Vitae

Personal Data

Name: Ullash Kumar Rout
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Education

1998-2000: Master of Technology in Electrical Engineering, Indian Institute of Technology, Kanpur, India.
1991-1995: Bachelor of Engineering in Electrical Engineering, IGIT Sarang, Orissa, India.
1990-1991: BSc in Physics Honours, S.C.S. College, Puri, Orissa, India (later switched to electrical engineering).
1988-1990: (10+2) in Science, S.C.S. College, Puri, Orissa, India.
1977-1988: Schooling (Primary, Upper Primary, Minor and High school).

Practical Training

1993-1993: Operation principle of ‘Talcher Thermal Power Plant’, Talcher, Orissa, India.
1994-1994: Design and construction of ‘132/33 kV electricity substation’, Bidanasi, Orissa, India.
1999-1999: Formulation and working of ISPLAN software package on Energy System Analysis, Asian Institute of Technology, Bangkok, Thailand.

Work Experience

2001-2006: Researcher, Energy Modeling Group, Institut für Energiewirtschaft und Rationelle Energieanwendung (IER), Stuttgart, Germany.
2000-2001: Senior Research Associate in Department of Electrical Engineering, Indian Institute of Technology, Kanpur, India.
1996-1998: Lecturer in Electrical Engineering Department (adhoc), College of Engineering and Technology, Bhubaneswar, Orissa, India.