# A HYBRID ENERGY-ECONOMY MODEL FOR ANALYSIS OF CLIMATE POLICY IN ASIA

by

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# ABSTRACT

This research involves the development and application of CIMS- Asia, a hybrid energy-economy model designed for the analysis of climate policy in non-OECD Asia. The hybrid CIMS framework is selected because it incorporates all of the elements that improve the usefulness of a model including technological explicitness, behavioural realism, and macroeconomic feedbacks. Regionally, CIMS-Asia represents all non-OECD countries of Asia, except China. Temporally, modelling simulations run from 2000 to 2050 in five-year intervals. The primary purpose of applying CIMS-Asia was to forecast how the energy system of non-OECD Asia would evolve under a reference case and with the application of GHG emission abatement policies. Reference run results from CIMS-Asia suggest that the region will account for 17% of global GHG emissions by 2050. Results from the policy runs suggest that although there are significant opportunities for emissions reduction, they are not relatively low cost as expected.

# ACKNOWLEDGEMENTS

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# GLOSSARY

AEEI        Autonomous Energy Efficiency Index

AMELA       Africa, Middle East and Latin America

BAU         Business as Usual

CCS         Carbon Capture and Storage

CGE         Computable General Equilibrium

$CO_2e$     Carbon Dioxide Equivalent

DA          Developing Asia – Refers to all non-OECD Asian countries excluding China

EIA         Energy Information Administration

EJ          Exajoule

EOR         Enhanced Oil Recovery

ESUB        Elasticity of Substitution

GDP         Gross Domestic Product

GHG         GHG

Gt          Gigatonne ($10^9$ tonnes)

IEA         International Energy Agency

IPCC        Intergovernmental Panel on Climate Change

LCC         Life Cycle Cost

MAC         Marginal Abatement Cost

| | |
|---|---|
| Mt | Megatonne ($10^6$ tonnes) |
| OPEC | Organisation of the Petroleum Exporting Countries |
| POLES | Prospective Outlook on Long-term Energy Systems |
| PPM | Parts Per Million |
| RPP | Refined Petroleum Product |
| UNFCCC | United Nations Framework Convention on Climate Change |

# CHAPTER 1: INTRODUCTION

## 1.1 Background

On November 17th 2007, the Intergovernmental Panel on Climate Change released the Fourth Assessment Report – Climate Change 2007. The report states that it is very likely (>90% probability) that the net effect of anthropogenic greenhouse gas (GHG) emissions since 1750 has been one of atmospheric warming (IPCC, 2007a). It goes on to state, that it is also very likely that continued GHG emissions at or above current rates will cause greater warming and changes to the climate system. Since pre-industrial times, global temperatures have increased by 0.6 degrees Celsius on average, and continue to increase. Climate scientists warn that an increase of two degrees Celsius above pre-industrial times may be a threshold, above which climatic risks may rapidly increase due to positive feedback mechanisms in the climate system (IPCC, 2007b).

Results of global climate models suggest that without significant emissions abatement, breaching the two degrees Celsius limit will occur well before the end of this century (IPCC, 2007b; Weaver, 2008). To avoid the risk of accelerated climatic risks, some researchers suggest emissions reductions of 50% below 2005 levels by 2050 are necessary (Weaver et al., 2008).

The release of $CO_2$ from fossil fuel use is the single greatest source of anthropogenic GHG emissions. As $CO_2$ is very long lived in the atmosphere, concentrations have increased from pre-industrial levels of 270 ppm to the current 385 ppm (IPCC, 2007a).[1] Due to the cumulative nature of $CO_2$ in the atmosphere, countries worldwide have varying degrees of responsibility for current atmospheric concentrations. A nation's responsibility is reflective of their total emissions released into the atmosphere

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[1] Weaver et al. (2008) estimate the radiative forcing effects of $CO_2$ to last in the order of tens of thousands of years.

since pre-industrial times. Therefore, developed nations have a greater responsibility for the current concentrations of GHG emissions than do developing regions. However, as the energy systems of developing regions grow, they too gain responsibility.

The countries of non-OECD Asia (excluding China), with a population of 2.1 billion and a rapidly growing energy system, represent a significant and growing source of global GHG emissions (see Appendix A for country list). At the rate of current growth, the expectation is that non-OECD Asia (hereafter the study region) will contribute a significant portion of the increase in global GHG emissions over this century. However, the study region is responsible for little of the current atmospheric GHG concentrations, and on a per capita basis has one of the lowest emissions rates in the world (Böhringer & Welsch, 2004).[2]

Anthropogenic climate change represents one of the most challenging global resource management issues presented to date. The first challenge is that the atmosphere is a common pool resource, characterized as being finite and difficult to exclude others from its use (Ward, 2006). Finite refers to the increasing climate risks associated with elevated concentrations of GHGs in the atmosphere. As the costs associated with climate change are not included in market transactions, a market failure occurs. Resource management problems involving market failures require effective policy solutions. The challenge is that nations that internalize the cost of emitting GHGs into the atmosphere, must share the benefit of reduced climate risk globally. This creates a disincentive for nations to act alone in reducing GHG emissions.

International climate agreements are the result of international efforts to address climate change as a common pool resource problem. Their initial purpose was to act as a platform for a collaborative international effort to reduce GHG emissions. The process began with the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, currently represented by191 member nations (UN, 1992). In order to create

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[2] Currently per capita emissions in the study region are 1.25 tonnes $CO_2$e/capita versus the global average of 4.22 $CO_2$e/capita.

binding targets, the Kyoto Protocol to the UNFCCC adopted in 1997, established targets for some industrialized member nations. The Kyoto protocol came into force in 2005, with a commitment period ending in 2010. Overall, the Kyoto protocol has had limited success in reducing net global emissions, with some researchers arguing that its net benefit may be zero due to limited membership and some targets being set too low for member nations (Böhringer; 2002).

The European Union Cap and Trade System provides an example of a regional target based climate agreement, initially established to assist European Union (EU) countries in meeting Kyoto targets. This agreement is a cap and trade system that applies to large industrial emitters of GHGs. To date, the trading scheme has had little impact on emissions reduction due to the over-allocation of permits. However, a recent study suggests that the trading scheme is working and that plans exist to reduce permit allocation (Ellerman & Joskow, 2008). Another example of a regional target based agreement is the Western Climate Initiative (WCI), first established in 2007 by the governors of four US states. Currently, WCI membership represents 73% of the Canadian economy, and 20% of the US economy.[3] Under the Western Climate Initiative, member states/provinces are bound to reduce GHG emissions to 15% below 2005 levels by 2020 (WCI, 2007).[4] The above are example of target-based agreements, designed to overcome the disincentive nations face for acting alone. As climate agreement themselves do not provide the necessary mechanisms for reducing GHG emissions, effective climate policies are needed.

Nations that ratify target-based agreements must then create domestic policies aimed at GHG emissions abatement. Common evaluation criteria for policy include environmental effectiveness, economic efficiency, political acceptance, administrative ease, and equity. Environmental effectiveness is a measure of the policy's ability to meet its environmental objective. Economic efficiency is a measure of the cost that society must bear to meet the environmental objective. Political acceptance measures the degree

[3] US membership includes California, Montana, New Mexico, Oregon, Utah, and Washington; Canadian membership includes British Columbia, Manitoba, Ontario, and Quebec.

[4] For a complete review of regional and international climate agreements see: Bodanski (2007).

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that the political system supports the policy. Administrative ease provides an indication of administrative requirements of a policy. Finally, equity is an overall measure of how the costs and benefits of a policy are spread among the actors involved (Ward, 2006). Applying these evaluation criteria to climate policy, researchers have found that policies that apply a direct charge on GHG emissions are the most effective, efficient, administratively easy, and equitable (Nordhaus, 2008).

The challenge for decision makers is in deciding, first, what international policy agreements to join and, second, what domestic policies to apply in order to meet agreed upon commitments. Given these challenges, decision makers need policy options that meet the evaluation criteria outlined above, and information on the outcomes of the policy options decades into the future. Energy economy models are tools developed to assist decision makers with both of these challenges, and ultimately to help create better policies.

## 1.2 Energy Economy Modelling

In general, the purpose of energy economy models is to provide decision makers with information about how an energy system will evolve over time with and without policy intervention. For decision makers faced with the challenge of creating domestic climate policies, energy economy models can provide information for each of the evaluation criteria described above.

Currently, one of the key applications of energy economy models is to estimate the interaction between economic activity, energy consumption, and the resulting GHG emissions over time (Peters, 2006). The analysis of climate policies requires forecasting the evolution of an energy system over time, under business as usual (BAU) and policy scenarios. Researchers worldwide have taken different approaches in developing energy economy models, with three modelling paradigms emerging as a result with varying strengths and weaknesses. The following section will explore the strengths and weaknesses of these paradigms, ultimately providing rationale for the approach adopted in this study.

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### 1.2.1 Modelling Approaches

Initially, energy economy modellers either followed a bottom-up or top-down approach in model development. Bottom-up models are those that evolved from physics and engineering type models, relying on a detailed representation of existing and emerging technologies available for satisfying energy service demands. Conversely, top-down models evolved from economic type models that rely on parameters to estimate aggregate relationships between costs and the inputs and outputs to an economy in an equilibrium framework (Jaccard & Rivers, 2005).

To measure the usefulness of an energy economy model, researchers have developed evaluation criteria that include behavioural realism, technological explicitness, and macroeconomic feedbacks (Jaccard, 2005). Technological explicitness refers to how well a model represents individual energy intensive technologies in an energy system, an asset for technology specific policies. Behavioural realism is a measure of how well a model reflects the actual behaviour of consumers and firms when making choices about investments in technologies or infrastructure. Finally, macroeconomic feedbacks are a measure of how well a model represents the change in production in one area of the economy due to a change in production elsewhere. This is important given that GHG abatement policies produce indirect spillover effects, resulting in feedbacks into other sectors of the economy (Loschel, 2002).

Applying these criteria to the traditional top-down and bottom-up approaches makes it clear that each has differing strengths weaknesses. The following discussion will highlight these differences from the perspective of researchers who aim to bridge the gap between the two approaches.

A top-down modelling approach relies on historic market data to create parameters that estimate the aggregate relationship between costs and other inputs to an economy, linking these to outputs in an equilibrium framework (Jaccard, 2005). One of the key parameters is autonomous energy efficiency improvement (AEEI), representing improvements in end-use energy efficiency of technologies not driven by changes in

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energy prices (Loschel, 2002). Through the reliance of parameters to estimate technologies, top-down models are not technologically explicit and therefore not as useful for technology-specific policy analysis. Another key parameter in the top-down framework are elasticities of substitution (ESUB), indicating the substitutability between any two pairs of aggregate inputs and energy forms. The ESUB parameters are derived from historic data and as such provide a certain degree of behavioural realism. A limitation of this approach is that the accuracy of such parameterization is dependant on the variability of past relationships being representative of those in the future (Jaccard, 2005). Research has shown that this limitation often results in modellers setting these parameters judgmentally, rather than from empirical evidence (Bataille, 2005). In terms of macroeconomic feedbacks, top-down models can score well if they achieve full market equilibrium.

Bottom-up models rely on detailed accounting of energy using technologies and infrastructure in an energy system. During model simulation, technologies and infrastructure offering the same service are near perfect substitutes competing for market share. Within the model, decision makers select the technology and infrastructure with the lowest discounted life cycle cost. Life cycle costs are primarily a function of a technologies capital costs, fuel costs and operating costs (Jaccard & Rivers, 2005). This approach scores well on the side of technological explicitness, requiring a detailed account of all current and future technologies and infrastructure. A limitation of this approach is the false assumption that consumers and firms select technologies based on the lowest discounted life cycle cost alone. Several studies have demonstrated that consumers and firms apply non-financial (intangible) costs in decisions making, based on a perception of quality and/or risk associated with a technology (Axsen, 2007). What results from such an approach is a consistent underestimate of the full social cost of technological change (Jaccard, 2005). Bottom-up models therefore score poorly in terms of behavioural realism in comparison to top-down models. Another shortcoming of the bottom-up approach is the partial equilibrium analysis, which does not capture the broader macro-economic effects of GHG abatement policies on the entire economy.

### 1.2.2 Hybrid Energy Economy Models

Hybrid modelling is a relatively new approach to energy-economy modelling, aimed at improving the usefulness of models though incorporating the strengths of both the top-down and bottom-up approaches. The hybrid approach represents efforts to improve how models incorporate technological explicitness, behavioural realism and macroeconomic feedbacks (Jaccard et al., 2003). The CIMS model is a hybrid energy-economy model, developed by the Energy and Materials Research Group at Simon Fraser University. CIMS is the outcome of continuous research efforts aimed at improving the technological explicitness, behavioural realism and macroeconomic feedbacks of the model. Chapter 2 provides a more detailed description of the structure and function of CIMS, including the methods applied in developing and applying CIMS-Asia.

Given the regional-international scope of this study, focus will turn hybrid energy-economy models that are global in scale. Melton (2008), found ten commonly applied global energy economy models that attempt to bridge the gap between top-down and bottom-up through a hybrid approach. A review of these approaches indicates that there is no single global model that completely incorporates technological explicitness, behavioural realism, and macroeconomic feedbacks. Although the CIMS framework performs well against these three criteria, it is not currently a global model.

### 1.2.3 The CIMS Global Project

The above sections demonstrate that there is a need for further research and development in the field of hybrid energy-economy modelling. Given the success of the CIMS model of incorporating key modelling characteristics (technological explicitness, behavioural realism, macroeconomic feedbacks), a unified research effort is underway to create a global framework of CIMS models. The strategy is to create several regional CIMS models linked into a global general equilibrium framework. Table 1 outlines the five complete modelling studies and the two remaining that are near completion. As mentioned this study involves the development and application of CIMS-Asia, covering all non-OECD nations of Asia (excluding China).

**Table 1:    Regional CIMS model definitions**

| Model | Regional Definition | Reference |
|-------|---------------------|-----------|
| CIMS AMELA | Africa, Middle East, and Latin America as one region | Melton, 2008 |
| CIMS Canada | Canada split into seven provincial sub-models | Jaccard et al.1996 |
| CIMS China | China as one region | Tu, 2005 |
| CIMS Asia | All non-OECD countries of Asia excluding China | Goggins, 2008 |
| CIMS EIT | Economies in transition, including all former Soviet Union and Eastern European countries | Wolinetz, 2008 (in progress) |
| CIMS OECD | All OECD not accounted for by other CIMS models as one region | Goldberg, 2008 (in progress) |
| CIMS USA | United States as one region | Tubbs, 2008 |

## 1.3 Project Rationale

GHG emissions arising from global energy systems pose a real and growing risk of accelerated climatic changes. Reducing GHG emissions to levels that scientists suggest is necessary requires effective policies. Energy economy models are tools that can inform decision makers about the likely outcomes of such policies decades into the future. The above also suggests that hybrid type models, such as CIMS, provide a more accurate and consistent message for decision makers than strict bottom-up or top-down models. In terms of scientific exploration, hybrid energy-economy modelling at the regional-global scale is a relatively new field of study. This study will contribute to both the ongoing theoretical and the applied work in the field of hybrid energy economy modelling.

Theoretical project rationale includes:

- challenging the current methodologies being applied by international energy economy models;
- contributing to the ongoing research and development efforts in hybrid energy economy modelling; and,

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- contributing to the growing body of theory on international climate policy.

Applied project rationale includes:
- creating a new tool capable of simulating the energy system of non-OECD Asia by producing reference case and policy forecasts;
- contributing to the current mix of climate policy options for non-OECD Asia with this new tool; and,
- contributing to the effort of making CIMS a global model, thus greatly expanding opportunities for applied research.

## 1.4 Research Objectives and Questions

This study involves the development of a hybrid energy-economy model for the non-OECD Asia region (hereafter CIMS-Asia) though the application of the CIMS framework. In addition, this research is part of an overriding research efforts aimed at creating a global linkage of regional CIMS models. The following are the specific research objectives and questions that this study aims to address:

**Research Objectives:**
1. To develop a CIMS type model that is representative of non-OECD Asia, capable of the analysis of climate policy to the year 2050.
2. To simulate how the energy system of non-OECD Asia will respond to climate policies by applying charges on GHG emissions using CIMS-Asia.
3. To contribute to the CIMS-Global project, a series of research efforts aimed at creating a global linkage of regional CIMS models.

**Research Questions:**
1. Does the BAU forecast provide opportunities for GHG emissions abatement in the study region?
2. Do the policy forecasts indicate that the abatement costs are lower in the study region relative to other regions of the world?

3. Are there low cost policy options that would result in the study region contributing to a global GHG emissions reduction target of 50% below 2005 levels by 2050?

To address the research questions and objectives outlined above, this paper includes five additional chapters. Chapter 2 provides more details on the structure and function of the CIMS model, and outlines the methodology followed in model development and application. Chapter 3 provides an overview of the energy system of the study region, setting the context for the challenges and opportunities that exist within the energy system for GHG emission abatement. Chapter 4 summarizes the modelling results generated to address the research questions and objectives of this study. Chapter 5 presents a discussion with a comparison of results from other studies to highlight methodological differences. Finally, Chapter 6 concludes and provides recommendations for policy makers and future research.

In addition, this study includes three appendices with supplemental information. Appendix A provides a country list and regional definition. Appendix B provides the exogenous stock forecasts for the 15 primary energy supply and demand sectors. Appendix C provides a detailed accounting of the model results generated during this study.

# CHAPTER 2: METHODOLOGY

The previous chapter provided the rational for applying the CIMS framework in
the analysis of climate policy within the study region. This chapter will turn the focus to
the structure and function of the CIMS model, and the methodology applied in this study.
Section 2.1 begins with a detailed description of the CIMS model, the model sequence
and the data requirements. Section 2.2 describes the model development approach taken
in this study, in light if the data needs and limited resources available. Section 2.3
provides an overview of that application of CIMS-Asia to analyse climate policy in the
study region. Finally, section 2.4 highlights the key uncertainties associated with the
results of this study.

## 2.1 The CIMS Model

The CIMS model is a result of efforts made by researchers at the Energy and
Materials Research Group to improve the behavioural realism and macroeconomic
feedback abilities of a bottom-up model (Jaccard et al., 1996). The current version of
CIMS is the result of over 15 years of research efforts focused on bridging the gap
between top-down and bottom-up models. The original CIMS model developed for
Canada is composed of 7 regional sub-models, representing over 2800 technologies, split
between 15 energy intensive sectors. For this project, a single region represents all 31
countries of study region. Currently, CIMS' time horizon is to 2050 at 5-year intervals.
To understand the methodology applied for the creation of CIMS-Asia, the following
outlines the model sequence, the market share equation, and the data requirements.

### 2.1.1 Model Sequence

CIMS is a simulation model, where the outcomes of policies are unknown until
the end of a model sequence. For example, to reach an emissions target at some point in

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the future, multiple iterations of policies are often required. The following outlines the model sequence of CIMS in six simplified steps (adopted from Rivers, 2008).

1. Initiation of CIMS starts with a set of base-case macroeconomic forecasts for each sector, set by the user out to 2050. The macroeconomic forecast represents the forecasted demand from each sector or sub-sector of energy-using goods or services. An example would be the forecasted demand for tonnes of steel within the iron and steel sector from 2005 to 2050.

2. In each five-year period, some portion of existing capital stock is retired according to its expected lifetime.[5] Declining output in a sector can also cause capital stock to be prematurely retired. Once capital stock has been retired, the output capability of the remaining stock is subtracted from the total demand of output to get the demand for new capital stock of a certain service type. For example, consider automobiles being retired after the average lifetime of 15 years.

3. Technologies with the same service capability compete for the demand of new capital stocks based on the market share algorithm, described in the following sections. The behavioural parameters of CIMS exist within this function to emulate how consumers and firms make decisions when purchasing new capital stocks. A more detailed discussion of the three behavioural parameters of CIMS appears in the next section.

4. A technology competition occurs again in a similar way to determine if any capital stocks are retrofitted or prematurely retired. This process is specific to larger facilities such as power plants or pulp mills that often undergo a retrofit rather than a complete retirement at the end of the facility's lifetime. As an example, consider the retrofitting of factories making large trucks into factories that make smaller cars, or closing completely.

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[5] Capital stock refers to technologies or infrastructure that has been invested in within the model framework. For example, investments in cars, dishwashers, coal plants, and electric motors are all forms of capital stock.

5. Next, iterations occur between the energy supply and demand modules and the macroeconomic module in each time-period, with prices and quantities adjusted slightly as they would by the market forces of supply and demand. The iteration continues until each supply and demand sector agrees on a price within 5%, resulting in CIMS being a partial equilibrium model.

6. The model sequence concludes with the generation of results for each five-year period of the 50-year model run. CIMS generates both aggregated and disaggregated reference and policy scenario results. Detailed results are available for energy supply and demand, energy costs, fuel mix, technology selection, GHG emissions, output, cost of production, and economy effects. Figure 1 below, depicts the model structure and sequence.
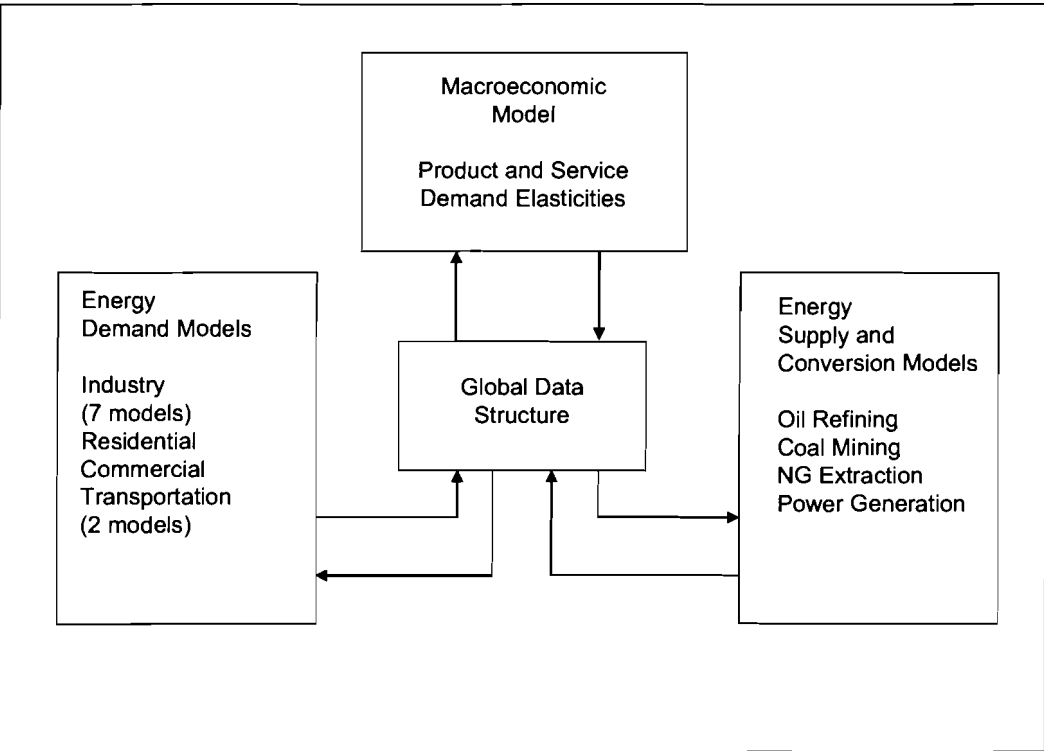


**Figure 1:    CIMS model structure and sequence**

### 2.1.2 Market Share Algorithm

CIMS is a technologically explicit model that tracks the evolution of technology stocks over time by estimating the retirement, retrofit and purchase of technologies. As described in the modelling sequence above, demand for energy intensive goods and services drives demand for new technologies. Demands for energy services occur at nodes within each sector, such as demand for person-kilometres-travelled of different types of personal transportation. Energy service nodes represent the "bottom" of the model where specific technology selection occurs. In each time-period, new technologies within a service node compete for market share based on the life cycle cost, according to the following formula:

$$MS_j = \frac{\left[ CC_j * \dfrac{r}{1-(1+r)^{-n}} + MC_j + EC_j + i_j \right]^{-v}}{\sum\limits_{k=1}^{K}\left\{ \left[ CC_k * \dfrac{r}{1-(1+r)^{-n}} + MC_k + EC_k + i_k \right]^{-v} \right\}}$$

| | | |
|---|---|---|
| $MS_j$ | = | market share of technology j for new equipment stocks at time t, |
| $CC_j$ | = | capital cost of technology j |
| $OC_j$ | = | operation and maintenance cost of technology j |
| $EC_j$ | = | energy cost of technology j |
| $r$ | = | discount rate (time preference) |
| $i_j$ | = | intangible costs and benefits that firms perceive of technology j |
| $v$ | = | variance parameter, representing market heterogeneity |
| $k$ | = | all other technologies competing to perform the same service |
| $n$ | = | equipment lifespan |

The market share formula represents the life cycle costs (LCC) of each technology within the square brackets, being a function of capital costs, operating costs, energy costs, intangible costs, and the discount rate. As discussed in Chapter 1, the limitation of bottom-up models is that they often treat consumers and firms as the

"economic individual" who is a rational, perfectly informed and self-interested actor. Empirical evidence demonstrates that this is not how consumers and firms behave when making decisions about investments in energy intensive goods and services (Rivers, 2005; Axsen, 2007). Researchers have worked to improve how accurately CIMS portrays consumers and firms by including the behavioural parameters in the market share formula. The three behavioural parameters of the CIMS model are intangible costs ('$i$'), discount rate ('$r$'), and variance parameter ('$v$').

The intangible cost parameter ('$i$') represents the non-financial benefits and costs that both consumers and firms apply to individual technologies (Axsen, 2006). It is not possible to measure intangible costs directly as they represent a consumer or firms' perception of the quality and/or risk associated with a technology. Measuring intangible costs requires market data and estimation techniques such as discrete choice surveys (Rivers, 2005; Axsen, 2007).

The discount rate ('$r$'), or time preference, is a measure of how much less value individual and firms apply to the future versus the present, normally simplified by an average percentage decrease per year into the future (Nyboer,1997). This is an important consideration for climate policy, as many technologies that reduce GHG emissions have higher capital costs offset by lower fuel and operating costs far into the future. Applying a high discount rate would reduce the benefits of future savings, therefore putting more weight on the capital cost of the technology. CIMS estimates the weighted average time preference that consumers and firms apply to decision making in terms of energy service demands. In researching discount rates for CIMS, Nyboer (1997) found that these parameters vary significantly depending on the technology and the consumer. For example, Train (1985) found that consumers often apply a discount rate as high as 80% in making decisions about new purchases. At the other end of the spectrum lies the social discount rate, in the range of 5% often applied by governments (Nordhaus, 2008).

The variance parameter ('$v$') represents the heterogeneity within markets, where consumers do not see technologies that provide the same service as being equal. For

example, consider the diversity of vehicles on the market that ultimately provide the same service at a similar cost. The variance parameter is an inverse power function that can mediate the life cycle cost (LCC) equation so that technology selection is not by least cost alone – a phenomenon known as penny switching. A relatively low 'v' indicates a more heterogeneous market, with even distribution of market share between technologies offering the same service.

Figure 2 indicates that as the variance parameter increases, the probability of choosing alternative 'A' versus 'B' increases indicating a less heterogeneous market.
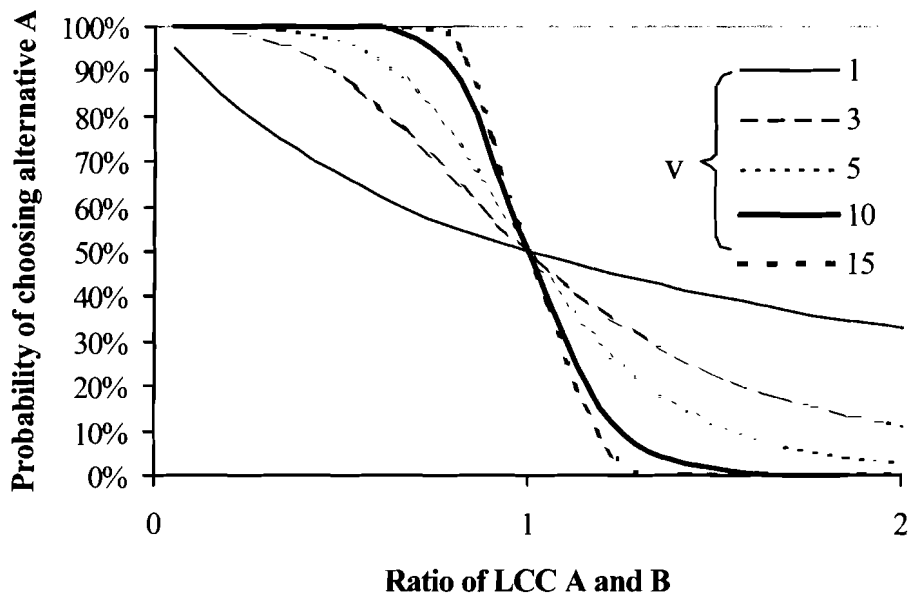


**Figure 2:    Variance parameter**

### 2.1.3 Data Requirements

As a technology explicit model that incorporates behavioural parameters and macroeconomic feedbacks, CIMS requires a large amount of data. These requirements include technology data, macroeconomic growth forecasts, macroeconomic feedbacks, and behavioural data.

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*Technology Data:* CIMS requires detailed technology information including costs (capital, fuel, operating), fuel use, output, emissions, and lifetime of all current and future technologies. CIMS also requires estimates for the intangible costs of each technology for the market share equation described above. Some technologies also require maximum market shares set to reflect physical limitations, as with large hydro dams. The technology stock in CIMS must be representative of all current and future technologies for the entire modelling period.

*Exogenous Macroeconomic Forecast:* Each of the 15 sectors requires an exogenous 50-year macroeconomic growth forecast for demand of energy intensive goods and services. Splits are also set within the model over the modelling period, dividing the sector level demand amongst the sub-sectors. An example would be splitting overall transportation demand into freight and personal. Another exogenous data requirement is the fuel prices for each sector, set over the modelling period to initiate the model sequence.

*Behavioural Parameters:* Data are required for the behavioural parameters described above, including discount rates, intangible costs, market heterogeneity. Nyboer (1997) found that it is possible to measure discount rates through market data. However, intangible costs and market heterogeneity must be measure indirectly using methods such as discrete choice surveys (Axsen, 2006).

## 2.2 Model Development Approach

The previous section has set the context for model development and application by providing details on the structure and function of the CIMS model, including the data requirements. This section focuses on the methods applied in developing the CIMS-Asia model, by populating the CIMS Canada framework with data from the study region.

As discussed in the Chapter 1, the CIMS Global project involves constructing regional CIMS models for the regions of the world not covered by the current Canada, USA, and China models. The four researchers tasked with this project aggregated the

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remaining countries of the world as the Economies in Transition (CIMS-ET), Africa - Middle East - Latin America (CIMS-AMELA), remaining OECD countries (CIMS-OECD), and non-OECD Asia (CIMS-Asia). Selection of these regions was strategic in terms of the availability of historic data, and forecasts from other energy economy models for comparison. The regions closely match those of the International Energy Agency (IEA), the primary source of international energy data found to be publicly available. As the primary source of international energy data, several models apply the same regional aggregation as the IEA. Examples include GMM (Barreto & Kypreos, 2006) and the POLES model (EC, 2006).

The first step was to determine the data requirements for developing the CIMS-Asia model. CIMS-Asia treats the study region as a single geographic region with 15 energy supply and demand sectors. The three primary and two secondary energy supply sectors are crude oil extraction, natural gas extraction, coal mining, and, petroleum refining and electricity respectively. The ten demand sectors are iron and steel, industrial minerals, metal smelting, mining, pulp and paper, other manufacturing, residential, commercial, transportation and chemical products. Each of the 15 energy supply and demand sectors requires data discussed in the previous section, averaged across the study region.

With the data requirements understood, the next step was to perform a literature review to determine data availability. The discovery was that data are limited for the study region at the level needed to populate the CIMS framework completely. A proposed solution was to contact modelling groups with similar data requirements to CIMS, with hopes of arranging data sharing agreements. Unfortunately, several attempts to access data from other energy economy modelling groups with data requirements similar to that of CIMS were unsuccessful. Further, a literature review was also unsuccessful in finding a methodology for estimation and/or extrapolation in the absence of reliable data. The assumption is that other groups must face similar data constraints, and therefore, likely rely on "educated guesses" that may not be acceptable within a peer-reviewed publication.

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For the development of CIMS-Asia, the methodology applied was to use Canadian data as a proxy where needed. Research into the major energy using technologies in the study region indicated that some technology mixes are very similar to that of Canada, largely due to a globalized economy. The assumption is that a competitive global marketplace encourages international companies to use the same technologies and infrastructure worldwide. In cases where data were not available at all, the selection of the most inefficient technologies from the Canada model served as a proxy. This assumption comes from an international comparison of industrial energy efficiency done by the International Energy Administration (IEA, 2007b). For example, the IEA found that the average efficiency of electric motors in India, are at the low end of the efficiency scale of those available in Canada.

In terms of setting the behavioural parameters for CIMS-Asia, Canadian figures served as a proxy. The rational for this approach is the assumption that cultural differences aside, consumers and firms likely behave similarly worldwide when considering investments. A sensitivity analysis on the behavioural parameters of CIMS-China supports this rational, as Tu (2004) found that model results are relatively insensitive to reasonable changes in behavioural parameters.

Overall, the most significant assumptions made during the modelling exercise involved setting the macroeconomic forecast to 2050. Some detailed forecasts were available to 2030, but very little data were available from 2030 to 2050. Between 2030 and 2050, the methodology applied was a simple extrapolation using the best available growth data for each sector or sub-sector. Once the CIMS-Asia model was populated, the next step involved calibrating the model to historic data. The year 2005 served as the base year, being the most recent year that historic data were available. Calibrating CIMS-Asia to historic data in 2005 only required minor adjustments to some of the sectors lacking data. A more detailed discussion of this process is presented in Chapter 4 along with results from the reference run.

## 2.3 Analysis

The first step in performing an analysis with an energy-economy model is to establish a business as usual (BAU), or reference run. The BAU represents the evolution of an energy system without the addition of any significant climate policies. The BAU is of significant importance, as it becomes the baseline to measure the effect of the policy runs. For the study region, no additional polices were added for the BAU. With the BAU established, the next step involved the simulation of GHG mitigation policies. These policies involved placing an emissions charge on GHG emissions within CIMS-Asia. Emissions charges represent a charge on emitting carbon dioxide equivalents ($CO_2e$), applied as additional operating costs for individual technologies.[6] Referring to the market share formula (Equation 1), emissions charges increase the life cycle costs of GHG intensive technologies. The outcome is that GHG intensive technologies eventually begin to loose market share with a high enough emissions charge. To generate the results needed for this study, iterations of emissions charges were required. The following section will describe and justify the model runs used in this study.

### 2.3.1 Model Runs Defined

The marginal abatement cost (MAC) curves presented in this study are the result of a carbon charge of $0 $tCO_2e$ applied in 2010 increasing linearly to $200 $tCO_2e$ in 2050 (see figure 3 next page). The year 2010 was the start date for emissions charges because it is unlikely that any developing countries will adopt such policies before that time. The gradually increasing emissions charge represents the expectation that a country will start at a low charge, and then gradually increase it over time providing consumers and firms with a clear price signal. A price signal is important as it provides consumers and firms with the foresight into the additional future costs associated with an emissions charge. The maximum emissions charge for creating the MAC curves was set at $200 $tCO_2e$. Charges above this level are unlikely by 2050, primarily due to the potential for the slowing of economic growth in the developing economies of the study region.

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[6] The CIMS model applies the IPCC protocol to convert process gasses, carbon dioxide ($CO_2$), nitrogen oxides ($N_2O$), and methane ($CH_4$) into a single measure of carbon dioxide equivalents ($CO_2e$).
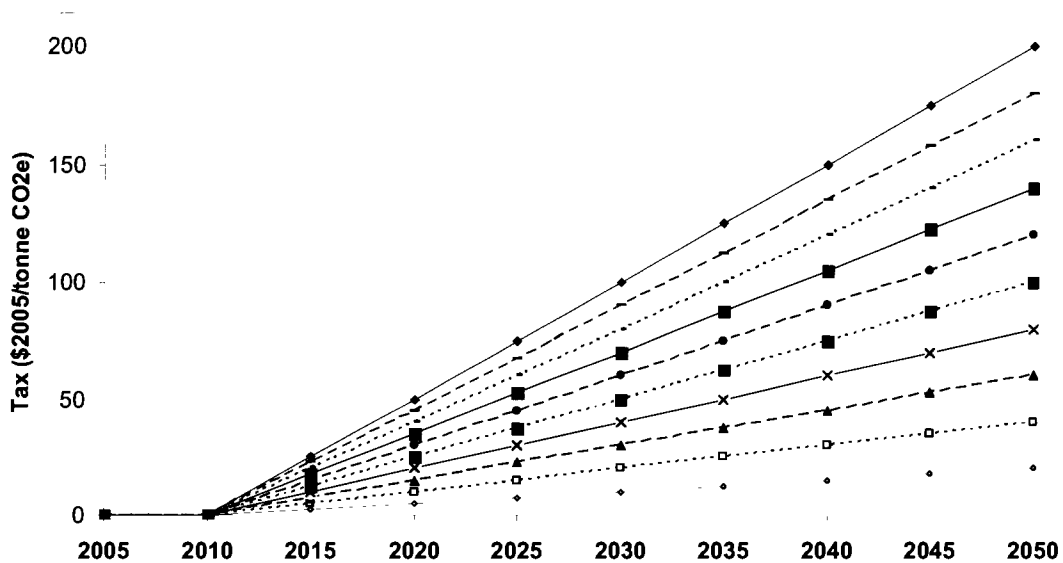
**Figure 3: CO2 price paths used to create MAC curves in 2050**

In addition to creating MAC curves, this analysis involved simulating various GHG emission price paths with CIMS-Asia. The rationale for this was to provide information on how the energy system of the study region would likely respond to policies cited in other studies. Further, it provided an opportunity to test CIMS-Asia as a newly developed tool for the analysis of climate policy in non-OECD Asia.

An international policy architecture that is popular from the perspective of developing countries is the "cap and convergence" architecture (Meyer, 2004; Mintzer et al., 2003). Nations start by "contracting" GHG emissions and then "converge" to a global per capita emissions target by a certain date. To create a domestic policy from this architecture, the convergence target of 1.89 tonnes $CO_2$e per capita was set for 2050. This target reflects a current global emissions estimate that could keep global temperature increase below 2.0 degrees Celsius to 2050 (Weaver et al., 2008). Emission charges began in 2015, gradually increasing over time to reach the above convergence target.

In an application of CIMS-Canada and CIMS-China, Bataille et al. (2008) provide a comparison of marginal abatement costs generated by both models. In this study, the emissions charge starts at $10/tonne $CO_2e$ in 2013 and increases exponentially to $100/tonne $CO_2e$ in 2050. Simulating this emissions price path provided an opportunity to create results comparable with other regional CIMS models.

The final policy target considered in this study is the stabilizing of GHG emissions at 2010 levels by 2050. Such a policy represents a strict target given the expected growth in the region. The rationale for modelling this policy is to estimate the effect of high emissions charges on the energy system. Initially, a target of 5% below 2005 levels by 2050 was set as a policy target. However, due to the high growth of the BAU to 2050, emissions charges above $400 $tCO_2e$ were required to meet this target. As previously mentioned, emissions charges of this magnitude are unlikely for the developing economies of the study region.

Table 2 (below) provides a summary of the model runs performed by CIMS-Asia in this study. It includes mention of two sensitivity analyses done to address some of the uncertainty associated with this research. The following section will highlight the key uncertainties associated with the results of the analysis, and efforts made to manage these uncertainties.

**Table 2:    CIMS-Asia model runs**

| Model Run | Parameters Adjusted | Research Question |
|---|---|---|
| Reference | No parameter adjustments<br><br>Expectation of the future without policy intervention | Question 1,<br><br>Baseline comparison for all questions |
| Marginal Abatement Cost Curves | 10 GHG emission price paths starting in at of US $0/tonne $CO_2e$ in 2010 and increasing linearly to 2050, to a maximum of US $200/tonne $CO_2e$ (see figure 3 below) | Question 2 |
| Contraction and Convergence target | Iterations of $CO_2e$ charges needed to stabilize emissions at a per capita emissions target of 1.89 tonnes $CO_2e$ per capita by 2050 | Question 2<br>Question 3 |
| Bataille et al. policy price path | Emissions charge of US $10/tonne $CO_2e$ starting in 2013 and increasing exponentially to US $100/tonne $CO_2e$ in 2050 | Question 2<br>Question 3 |
| Stabilize Emissions at 2010 levels by 2050 target | Iterations of $CO_2e$ charges needed to stabilize emissions at 2010 levels by 2050 | Question 2<br>Question 3 |
| Sensitivity Analysis 1 | Adjusted macro-economic stock forecast of all sectors to test effects on marginal abatement costs | Tests sensitivity of all results |
| Sensitivity Analysis 2 | Adjusted the availability date of widespread carbon capture and storage technologies to test effects on marginal abatement costs | Tests sensitivity of all results |

## 2.4 Uncertainty

All forecasts are uncertain. The assumption is that the uncertainty increases with the complexity of a system, and the distance forecasted into the future. This analysis involves generating forecasts decades into the future with an energy-economy model designed to represent 31 developing countries as a single region. Clearly, there are large degrees of uncertainty associated with the results of this study. The purpose of this section is to highlight the key uncertainties of this project, and ultimately present the argument that modelling frameworks are useful for managing uncertainty.

**Data Uncertainty**

The data required for this project were either historic or forecasted, with the latter generally involving more uncertainty. The forecast data needed for this project are highly uncertain, generally being the forecasts generated by other energy-economy models. One of the greatest uncertainties facing all forecasters is future economic growth. A method

of addressing this uncertainty is to update the forecast data within a model on a regular basis. The historic data used in this modelling exercise are also uncertain, being susceptible to measuring and reporting errors. Where data were missing, the extrapolation and interpolation needed also increased uncertainty.

## Structural Uncertainty

Structural uncertainty is associated with the fact that a model is a simple abstraction of a very complex system. The uncertainty arises from not knowing how accurately the model represents the actual system (Morgan & Henrion, 1990). The structural uncertainty is relatively high for this study, given the use of a single modelling framework to represent 31 developing countries as a single region.

## Parametric Uncertainty

Parametric uncertainty is associated with the variation that exists between a physical process, and how well the model mathematically represents that same process (Morgan & Henrion, 1990). The behavioural parameters of CIMS provide an example. For this study, the parametric uncertainty is high as Canadian parameters served as a proxy for the study region.

## Managing Uncertainty

In the context of energy-economy modelling, uncertainty will always be prevalent. The goal of this analysis was to be explicit about uncertainties, and to perform a systematic sensitivity analysis on some of the key assumptions. During this analysis, managing uncertainty involved the following efforts:

- *Applying a trusted modelling framework.* CIMS is a well-established and trusted framework for climate policy analysis. Applying a trusted framework helped to reduce some of the structural and parametric uncertainty associated with developing a new model.
- *Using data from trusted sources.* All of the data used to populate the CIMS framework were from trusted sources, helping to reduce data uncertainty.

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- *Testing key assumptions in a sensitivity analysis.* In the development of other regional CIMS models, researchers tested several of the key assumptions made in applying the CIMS framework including behavioural parameters, fuel prices, nuclear, and nuclear availability. This analysis complimented these efforts with a sensitivity analysis of the exogenous stock forecast and the availability of carbon capture and storage.

- *Calibrating results to historic data.* Because CIMS-Asia generates results for 2005, it is possible to perform a calibration back-cast to historic data with every model run. Matching results to historic data reduces uncertainty.

- *Comparing model forecasts with those of other models.* Comparing the reference forecast of CIMS-Asia to those of other energy economy models is another effort aimed at managing uncertainty. When model forecasts differed significantly, it offered an opportunity to catch modelling errors and to explore differing methodologies.

- *Being explicit about uncertainties and limitations.* The first step in managing uncertainty needs to be an open and explicit approach, as illustrated by this section. Further efforts for addressing the uncertainty associated with CIMS-Asia are the recommendations for further research presented in final chapter of this study.

# CHAPTER 3: ENERGY SYSTEM OF NON-OECD ASIA

In the previous chapter, a description of the CIMS framework illustrates the methods followed to develop and apply CIMS-Asia. The CIMS-Asia region represents the 31 countries of non-OECD Asia (excluding China) as defined by the International Energy Agency (see Appendix A). Section 3.1 begins by outlining general economic and demographic indicators that influence the energy system of the study region. Section 3.2 provides an overview of end-use energy demand in each of the major sectors in the study region. Section 3.3 outlines the total primary energy demand of the study regions' energy system. Section 3.4 summarizes the total greenhouse gas emissions from the study region. Section 3.5 describes some of the key energy conversion technologies of CIMS. Finally, Section 3.6 provides information on the status of carbon capture and storage (CCS) in the study region. Unless otherwise noted, all statistics are from 2005 – the most recent date that widespread energy data were available for the study region.

## 3.1 General Economic Trends

The rate of increase in population and economic output are important indicators of future energy demand, specifically in regions with very low per capita energy demand. The following section will highlight these trends in the study region, illustrating its growing global significance in terms of population and economic output. In 2005, the population of the study region was approximately 2.1 billion (world 6.5 billion) with 40% (world 50%) living in urban areas. By 2050, the study regions' population is forecasted to grow to 3 billion (world 9 billion) with roughly 60% (world > 60%) living in urban areas (UNDP, 2007). These projections suggest that roughly one billion additional people will join the urban population of the study region by 2050. Unlike developed nations, urban populations of developing nations demand far more energy intensive services and products than do their rural counterparts. For example, although rural households in India make up over 70% of the population, they account for only 42% of

the residential demand for oil, gas and electricity (IEA, 2007a). Rural populations in poor regions generally move to urban areas in search of higher paying employment and increased access to services (UN, 2006).

In terms of energy demand, rapid increases in the average per capita wealth of the region add to the effect of population growth. In 2005, the GDP of the study region in terms of purchasing power parity (PPP) was roughly 5 trillion (world 54 trillion), or $2380 per person. Forecasts suggest that by 2050 GDP (PPP) of the study region will reach roughly $30 trillion (world $180 trillion), or $10 000 per person (IMF, 2007). Between 2005 and 2030, forecasts suggest the economy will grow at 5.0% annually on average (EIA, 2007a). Forecasts for population and economic growth to 2050 suggest that the population will grow by one billion people and GDP/capita will increase by 400% (see Figure 4).
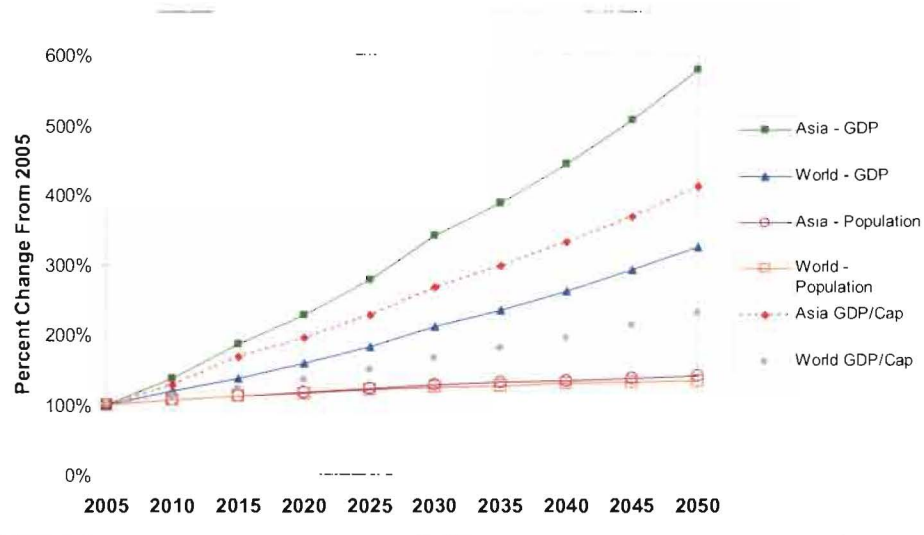


**Figure 4:    Projected growth in population and GDP comparisons**
Source: IMF (2007) & UNDP (2007)

High economic growth rates, population increase, and the rural-urban shift are drivers in the increase in demand for energy and energy intensive products in the study region to 2050.

## 3.2 Final Energy Consumption

The purpose of the previous section was to illustrate some of the drivers in the growth of the energy system over the modelling period. In this section, the focus will turn to the historic final energy consumption for each sector, setting the context for the projections presented in the next chapter.

Final energy consumption represents the total energy demand of end-use sectors. In 2005, the final energy consumption for the study region was 38.5 EJ, if biomass use is included. India was the single largest contributor at 16.5 EJ, compared to 22.0 EJ for the 30 remaining countries of the study region. Figure 5 provides a comparison of final energy consumption for both India and the rest of Asia.
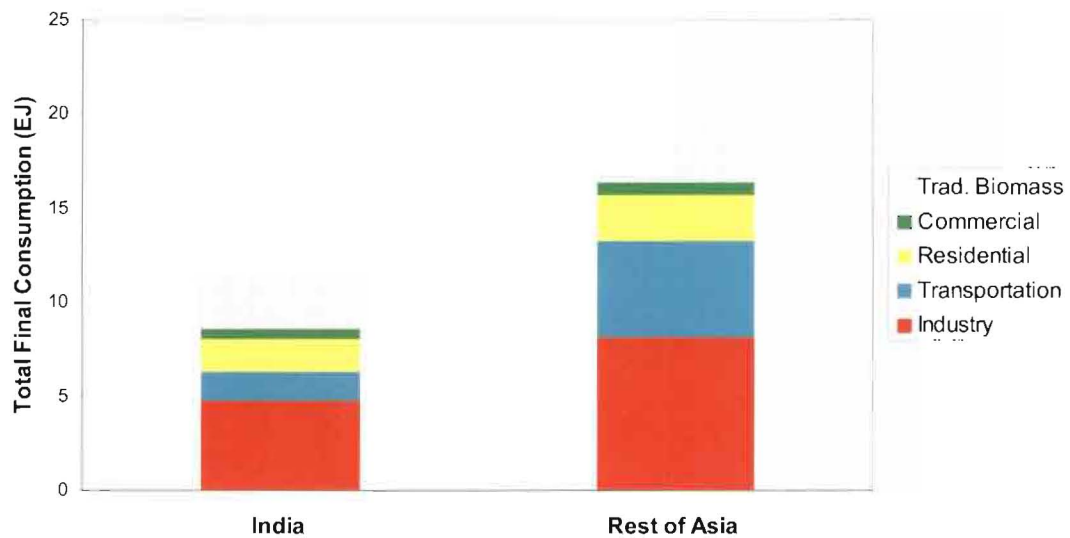


**Figure 5:    Total final energy consumption in India and Rest of Asia, by sector**
Source: IEA(2007a)

Biomass is included in the graph to highlight its significance in the energy system of the study region, making up 35% of total final consumption. Removing biomass from the total decreases final energy consumption in the region by 13.6 EJ. Such a significant decrease is due to the roughly 1.4 billion people in the study region who rely on biomass resources for their primary source of fuel for cooking (IEA, 2006a). To put this in

perspective, the IEA estimates the total world population relying on biomass for cooking to be roughly 2.5 billion people. For example, in India, 88% of rural residential energy use is from traditional biomass (IEA, 2007a).

Biomass was not included in this modelling exercise for the following reasons. First, the majority of biomass use in the study region occurs within an informal economy where individuals collect wood and animal waste for cooking, presenting challenges for inclusion in a modelling framework such as CIMS where relative costs are important. Second, since there are no records of transaction with wood and animal waste collection, the quality of data on biomass use is poor. Third, combustion of biomass is often GHG neutral depending on fuel type, combustion process and the re-growth of new biomass (IEA, 2006a).

By sector, final energy consumption in the study region is similar to other developing regions of the world. Typically, final energy consumption in developing regions is weighted towards industrial and agricultural production, versus commercial, transportation, and residential services (IEA, 2007a). The difference is likely due to developed regions having a more developed service based economy. Table 3 indicates that the industry sector dominates the energy system, representing over half of final energy consumption in 2005. The commercial sector accounts for only 5% of final energy consumption, with transportation and residential accounting for 25% and 18% respectively. A comparison of India to the rest of the study region (Rest of Asia) indicates that the only significant difference is a higher demand for transportation in the Rest of Asia.

**Table 3:** Final energy consumption in India, the rest of Asia, and the "study region", by sector in 2005 (EJ)*

|  | Industry | Commercial | Residential | Transport | Total |
|---|---|---|---|---|---|
| India (EJ) | 4.7 | 0.5 | 1.8 | 1.6 | 8.5 |
| *India Sector (%)* | *55* | *6* | *21* | *18* | *100* |
| Rest of Asia (EJ) | 8.1 | 0.7 | 2.5 | 5.1 | 16.4 |
| *Rest of Asia Sector (%)* | *50* | *4* | *15* | *31* | *100* |
| Study Region Total (EJ) | 12.8 | 1.2 | 4.2 | 6.7 | 24.9 |
| *Study Region Sector Total (%)* | *52* | *5* | *18* | *25* | *100* |
| Region Growth (%)** 2005-2030 | 2.5 | 4.5 | 2.6 | 2.9 | 3.2 |
| World Growth (%)** 2005-2030 | 1.7 | 1.5 | 1.4 | 1.6 | 1.6 |

Source: IEA, 2007a          *Biomass is not included          **Average % growth per year

With final energy consumption by sector understood, it would be interesting to compare the fuel mix with that of more developed regions for comparison. Table 4 (below) indicates that, in both the study region and OECD countries, roughly half of end use energy consumption is in the form of refined petroleum products. However, the study region differs significantly from OECD countries in the consumption of all other fuels. In the study region, the relative consumption of coal and biomass is significantly higher than the OECD total. Conversely, the OECD total consumption of gas and electricity is significantly higher than in the study region. The rationale for the difference is that the study region lacks distribution infrastructure for gas and electricity, coupled with the fact that biomass and coal are lower cost forms of energy (IEA, 2006a). Electrification rates presented in section 3.3.2 support this argument.

**Table 4:** Final energy consumption in the study region and OECD countries, by fuel in 2005

|  | Coal | Petr. | Gas | Elec. | Biomas | Total |
|---|---|---|---|---|---|---|
| Study Region - Final Consumption (EJ) | 4 | 13 | 2 | 4 | 4 | 27 |
| *Percent of Total (%)* | *13* | *49* | *8* | *15* | *14* | *100* |
| OECD Average – Final Consumption (EJ) | 5 | 84 | 31 | 32 | 8 | 160 |
| *Percent of Total (%)* | *4* | *53* | *20* | *21* | *5* | *100* |

Source: IEA, 2007a

### 3.2.1 The Industrial Sector

In 2005, the industrial sector was responsible for 52% of final energy consumption in the study region. From 1990 to 2005, energy demand grew rapidly in the industrial sector at roughly 5% per year, versus 1% per year in OECD countries (IEA, 2007a). Table 5 shows that the primary energy source in the industrial sector is oil (30%), followed by coal (25%), electricity (16%), and gas (15%).

**Table 5:    Industrial sector end-use energy demand by fuel for 2005**

|  | Oil | Gas | Coal | Electricity | Total |
|---|---|---|---|---|---|
| Study region | 3.9 | 1.9 | 3.2 | 2.0 | 12.8 |
| *% of total* | *30* | *15* | *25* | *16* | *100* |

Source: (IEA, 2007a)

CIMS-Asia disaggregates the study region's industry sector into eleven industry sub-sectors, each producing a variety of energy intensive commodities (see Table 6). Table 6 separates the sub-sectors into two broad categories, manufacturing and fossil fuel production. The International Energy Agency (2007b) provides total end-use energy consumption from each of the manufacturing sectors. Table 6 indicates the three most significant of these are chemical products (26%), iron and steel (12%), and industrial minerals (10%). Non-specified end-use energy accounts for 41% of the total, providing evidence of the poor data availability for the region given that the IEA is the foremost authority on international energy statistics. Data availability was also poor for the petroleum producing sub-sectors in terms of end-use demand. Although CIMS does not require energy end-use data as an input, the above does provide evidence of the lack of data for the study area. CIMS does however require historic commodity outputs for each sub-sector in the base year, as well as forecasts to 2050. Historic commodity output data were more readily available and compiled from a number of sources.

**Table 6: Industry sub-sector output and end-use energy consumption in the study region for 2005**

| Manufacturing Sub-Sectors | Major Products Modelled | End-use energy (EJ) | % Total |
|---|---|---|---|
| Chemical Products | Ammonia, methanol, chlorine, sodium hydroxide, industrial gases, soda ash and petrochemicals | 3.30 | 26 |
| Industrial Minerals | Cement, lime, glass and bricks | 1.22 | 10 |
| Iron and Steel | Slabs, blooms and billets | 1.46 | 12 |
| Metal Smelting | Lead, copper, nickel, titanium, magnesium, zinc and aluminium | 0.03 | 0.2 |
| Mining | Mined ore and potash | 0.10 | 1 |
| Pulp and Paper | Newsprint, linerboard, uncoated and coated paper, tissue and market pulp | 0.20 | 2 |
| Other Manufacturing | Covers industrial activity not accounted for by other sub-sectors | 1.12 | 9 |
| Non-Specified | | 5.21 | 41 |
| Total | | 12.56 | 100 |
| Petroleum Sub-sectors | Major Products Modelled | End-use energy (EJ) | % Total |
| Coal Mining | Coal | n.a. | - |
| Crude Oil | Conventional and unconventional crude oil | n.a. | - |
| Natural Gas Extraction | Conventional natural gas and coal bed methane | n.a. | - |
| Petroleum Refining | Refined petroleum products | n.a. | - |

Source: IEA (2007b)

### 3.2.2 The Transportation Sector

In 2005, the transportation sector accounted for 25% of final energy consumption in the study region at 6.7 EJ. Combustion of diesel and gasoline account for 99% of fuel consumption, with 1% attributed to natural gas (Table 7). The use of biofuels and electricity was very limited as of 2005. However, several countries in the region are developing biofuel resources (IEA, 2007a).

**Table 7: Transportation end-use energy demand in the study region by fuel for 2005**

| | Oil | Gas | Electricity | Biofuels | Total |
|---|---|---|---|---|---|
| Study Region | 6.6 | 0.1 | 0.0 | 0.0 | 6.7 |
| % of total | 99 | 1 | 0 | 0 | 100 |

Source: (IEA, 2007a)

To compare the vehicle stock, Table 8 shows the personal stock split between motorcycles (70%), light duty vehicles (28%) and 3-wheel vehicles (2%). On a per capita basis, personal vehicle ownership is less than half the world average, and roughly 10% of the North American average. Fuel economy is lower in the study region than North America, averaging 8.7 litres/100km versus 9.6 litres/100km respectively (IEA/WBCSD, 2004). However, transportation demand is forecasted to grow at 4-6% annually to 2015 versus the 2% global average (IEA, 2007a). The rapid growth in transportation is attributed to the high economic growth in the region. Empirical evidence indicates a non-linear relationship between vehicle ownership and per capita income (Chamon et al., 2008). The relationship follows a sigmoid curve, with an exponential increase occurring at a threshold at roughly US $5000 per person in 2000 prices.

**Table 8:** **Vehicle ownership in the study region, world and North America by class for 2005**

| Vehicle Class | Personal Stock Study Region (millions) | Study Region % of Total | Per 1000 people – Study Region | Per 1000 people– World | Per 1000 people – North America |
|---|---|---|---|---|---|
| Light Duty | 38.7 | 28 | 18 | 114 | 630 |
| 2 Wheel | 98.3 | 70 | 47 | 34 | 13 |
| 3 Wheel | 3.9 | 2 | 2 | 1 | 0 |
| Total | 140.9 | 100 | 67 | 149 | 643 |

Source: (IEA/WBCSD, 2004).

CIMS models transportation demand as personal or freight, requiring inputs of the total demand for person kilometres travelled and tonnes kilometres travelled respectively. Freight demand is further split into ship, rail and truck. Personal demand is split by private vehicles, buses, rail and air transport. All of the data for this sector was available through the Sustainable Mobility Project (SMP), a transportation model developed by the International Energy Agency (IEA/WBCSD, 2004).

### 3.2.3 The Residential Sector

In 2005, the residential sector was responsible for 4.2 EJ of end-use energy demanded, 18% of total final energy consumption in the region. If biomass is included, the residential sector accounts for 14.6 EJ of end-use energy demand, an estimated 38% of total final energy consumption. As discussed above, this study follows the IEA's rationale for not including GHG emissions from biomass. As table 9 indicates, oil is the dominant fuel demanded by the residential sector, used primarily for cooking. Due to very low electrification rates in several countries within the region, electricity only represents a 34% share of end-use demand, (IEA, 2007a). Coal and gas have an equal share of 7% each, both used primarily for cooking.

**Table 9:    Residential sector end-use energy demand by fuel for 2005**

|  | Oil | Gas | Coal | Electricity | Total |
|---|---|---|---|---|---|
| Non-OECD Asia | 2.2 | 0.3 | 0.3 | 1.4 | 4.2 |
| *% of total* | *52* | *7* | *7* | *34* | *100* |

Source: (EIA, 2007a)

Electrification rates in the region are among the lowest in the world, second to only Africa. Table 10 (below) illustrates that the average electrification rate for the study region was roughly 56% in 2005. In total, the IEA estimates that over 900 million people in the study region do not have there homes connected to an electrical grid.[7] Estimates indicate over half of this population is in India due an electrification rate of 56% and a population of over one billion people. Singapore is the only country in the study region to claim full electrification, with Thailand and Malaysia being very close at 99% and 98% respectively. For South Asia, the IEA (2006a) estimates the rural and urban electrification rates to be 45% and 70% respectively.

In 2005, the estimate for the housing stock in the study region was roughly 150 million households. This figure was estimated by comparing floor space per capita to estimates on rooms per household using data obtained from Euromonitor International

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[7] These figure are estimates generated by the IEA and do not account for informal electricity grids or non-authorized connections that may exist

(2008). To model household energy use, CIMS-Asia requires estimates for space cooling, as well as common appliance usage. Space heating was not modelled due to the tropical climate of the study region. Household data were available through Euromonitor International (2008) and the Asia Development Bank (2008) for some countries within the region. The data were used to create the "average" household in the study region, and extrapolated across the entire housing stock.

**Table 10:    Electrification rates for select countries within the study region**

| Country | Electrification rate (%) | Population without electricity (millions) | Population with electricity (millions) |
|---|---|---|---|
| Cambodia | 20% | 10.9 | 2.7 |
| DPR Korea | 22% | 17.7 | 5.0 |
| Indonesia | 54% | 101.2 | 118.8 |
| Malaysia | 98% | 0.6 | 24.7 |
| Mongolia | 65% | 1.0 | 1.8 |
| Mayanmar | 11% | 45.1 | 5.7 |
| Philippines | 81% | 16.2 | 66.8 |
| Singapore | 100% | 0.0 | 4.3 |
| Thailand | 99% | 0.6 | 64.1 |
| Vietnam | 84% | 13.2 | 70.3 |
| Other Asia | 82% | 8.3 | 37.9 |
| East Asia Total | 64% | 214.8 | 402.1 |
| | | | |
| Afghanistan | 7% | 27.0 | 2.0 |
| Bangladesh | 32% | 96.2 | 45.3 |
| India | 56% | 487.2 | 607.6 |
| Nepal | 33% | 18.1 | 8.9 |
| Pakistan | 54% | 71.1 | 83.5 |
| Sri Lanka | 66% | 6.7 | 13.0 |
| South Asia Total | 52% | 706.3 | 760.3 |
| | | | |
| Study Region Total | 56% | 921.1 | 1161.9 |
| Africa | 38% | | |
| Latin America | 90% | | |
| Middle East | 78% | | |

Source: IEA (2006a)

### 3.2.4 The Commercial Sector

In 2005, the commercial sector accounted 1.2 EJ of total final energy consumption, only 4% of the total. As described above, the rationale for the low energy demand is developing regions generally having a less developed commercial sector. However, the forecast for annual growth rate for the study area is 4.5% to 2030, three times the world average (IEA, 2007a). Growth in this sector keeps pace with general economic growth forecasted for the same period. Table 11 indicates that electricity represents 62% of the sectors fuel demand, due to a need for lighting, space cooling, and appliances. Commercial electricity demand is almost twice that of the residential sector, likely due to commercial buildings being located in areas with energy distribution infrastructure. The remaining 38% of fuel demand is split between oil (15%), gas (15%), and coal (8%). These fossil fuels are demanded for space cooling, hot water, and cooking.

**Table 11:    Commercial sector end-use energy demand by fuel for 2005**

|  | Oil | Gas | Coal | Electricity | Total |
|---|---|---|---|---|---|
| Non-OECD Asia | 0.2 | 0.2 | 0.1 | 0.8 | 1.3 |
| % of total | 15 | 15 | 8 | 62 | 100 |

Source: (EIA, 2007a)

CIMS requires estimates of total floor space demanded by the commercial sector, further split into floor space estimates for various commercial building types over the entire modelling period. As floor space data were unavailable, the solution was to match energy consumption data provided for the entire sector. First, average building types were created for each sub-sector. Second, iterations of total floor space were simulated to match total final energy consumption reported for the study region. The Energy Information Administration (2006), Euromonitor International (2008), and the Asia Development Bank (2008) provided data on end-use energy demand for the commercial sector. The exogenous stock forecasts to 2050 were created with a simple extrapolation using available growth rates for the sector.

## 3.3 Total Primary Energy Demand

In the previous section, a discussion highlighted total final energy consumption for each of the major sectors in the study region. In this section, the focus turns to total primary energy demand, being the amount of site consumption, plus losses in the generation, transmission, and distribution of energy (IEA, 2007a).

In 2005, total primary energy demand was 38.3 EJ, roughly 7% of the world total 480 EJ (see Table 12).[8] Oil, coal, and natural gas account for 95% of total primary energy demand at 43%, 36%, and 16% respectively. The low GHG primary energy sources nuclear, hydro, and renewables account for only 5% of the total. Forecasts indicate total demand for primary energy increases at 3.2% annually to 2030, twice the rate of the world average (IEA, 2007a).

**Table 12:    Total primary energy demand in the study region by fuel in 2005**

|  | Coal | Oil | NG | Nuclear | Hydro | Ren. | Total |
|---|---|---|---|---|---|---|---|
| TPED* (EJ) | 13.0 | 16.5 | 6.7 | 0.7 | 0.7 | 0.6 | 38.3 |
| *Percent of Total (%)* | *36* | *43* | *16* | *2* | *2* | *1* | *100* |
| Region Growth (%) 2005-2030 | *5.0* | *4.1* | *5.6* | *8.0* | *5.5* | *15.0* | *3.2* |
| World Growth (%) 2005-2030 | *3.3* | *1.7* | *2.6* | *1.1* | *2.7* | *9.0* | *1.6* |

Source: (IEA, 2007a)    *Total Primary Energy Demand

Recall that the total final consumption by sector was relatively similar when comparing India to the rest of the study region (figure 4 above). In contrast, there is a significant regional difference in primary energy demand by fuel when comparing India and the rest of the study region. Figure 5 indicates that coal represents 55% of total primary energy demand in India, compared to 20% in the Rest of Asia. A much higher demand for oil and gas from the Rest of Asia than in India offsets the difference.

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[8] If biomass is included the total primary energy demand for the study region increases by 16 EJ to 54.3 EJ total.
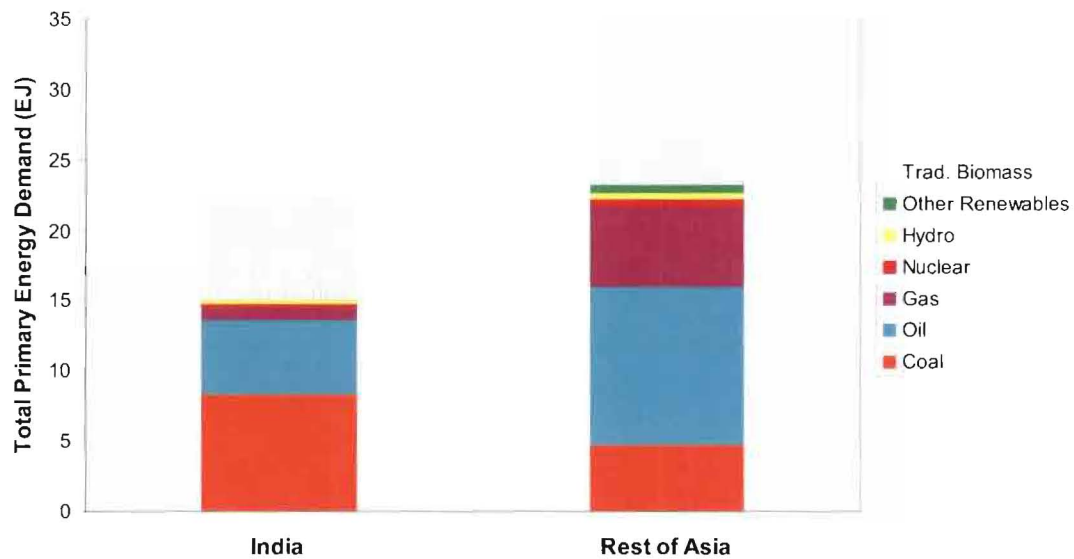
**Figure 6:** **Total primary energy demand in India and the Rest of Asia by fuel in 2005**
Source: IEA(2007a)

### 3.3.1 Coal

In 2005, Coal represented 13% of end-use demand and 34% if total primary energy demand in the study region. Forecasts for 2005 to 2030 indicate that the total primary energy supply of coal will grow at roughly 3.6% annually, twice the global average. The region is a net exporter of coal, with known coal reserves of 147 billion tonnes, 11% of the world total. At current consumption rates, the reserve to production ratio is over 200 years (IEA, 2007d). A challenge is that over 99% of the coal reserves are brown coal (lignite), which has a lower energy value and higher ash, sulphur, and moisture content than hard coal.[9] As a result, GHG emissions are higher given the need to burn more coal per unit of energy produced. Coal washing helps to reduce GHG emissions through removal of pyritic sulphur with a float/sink separation to enhance combustion efficiency and reduce potential pollutants. Currently coal washing is minimal in the region, with the percent of coal washed in India decreasing from 13% to 6

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[9] The IEA (2006a) defines brown coal as being lignite or sub-bituminous coal with a gross calorific content of less than 5700 kcal/kg, and hard coal having a gross calorific content of greater 5700 kcal/kg on an ash free and somewhat moist basis.

% between 1995 and 2000 (IEA, 2002). The predominant use of brown coal is to create steam for industry and power production.

### 3.3.2 Oil

In 2005, crude oil represented 49% of total primary energy demand and 43% of end-use demand in the study region. Proven reserves total 20 billion barrels, a 6.5-year supply at current consumption rates, assuming no imports (IEA, 2005). Domestic production of crude oil only satisfied 45% of the 8.6 mb/d demand in 2005. Forecasts suggest reliance on imports increases from 5.7 mb/d in 2005 to 12.2 mb/d by 2030. The main oil producing countries with the region are Indonesia, Malaysia, India, and Vietnam, all of which are now net importers of oil (IEA, 2005). Offshore oil currently accounts for roughly 30% of production in the region. Forecasts suggest offshore production will increase in the future, as the majority of unexplored sedimentary basins are offshore (IEA, 2005).

### 3.3.3 Natural Gas

As of 2005, the study region had proven reserves of natural gas estimated at 9.3 trillion cubic meters, 5% of the world total. Consumption in 2005 was 230 billion cubic meters or roughly 17% of total primary energy demand. Production in 2005 was 264 billion cubic meters, making the region a net exporter of natural gas with a reserve to production ratio of roughly 55 years (IEA, 2007a).

### 3.3.4 Nuclear Power

In 2005, the installed capacity of nuclear power was 8 GW, providing roughly 2% of the total primary energy demand. South Korea, Pakistan, and India are the only countries in the study region with significant nuclear production. The region has very small uranium reserves, producing less than 1% of the world supply as of 2005 (BP, 2003). Although growth rates are high in some countries, there are political limitations on the development of nuclear power facilities in much of the study region. These limits

were modelled by applying a maximum market share based on estimates made by the IEA (2007a).

### 3.3.5 Hydro

In 2005, the study region had 62 GW of installed hydro capacity, generating 0.5 EJ of electricity. Half of the installed capacity (31 GW) is in India, supplied from large-scale dams (IEA, 2007a). As with the other renewables, there are physical limitations on large hydro sites in the study region. Estimates suggest the maximum capacity in the region is 82 GW (IEA, 2007a).

### 3.3.6 Renewables

Renewable sources of energy considered in this study include biomass, wind, solar, and geothermal. Combined, these accounted for 1% of total primary energy demand with 5 GW of installed capacity, producing 0.11 EJ of energy in 2005. As discussed, traditional non-commercial biomass is not included in this study. Only biomass used in commercial and industrial processes is considered.

## 3.4 GHG Emissions

GHG emissions considered in this study include process emissions, carbon dioxide, nitrogen oxides, and methane. This study does not consider emissions from land-use changes, agriculture, or waste. GHG emissions from the study region totalled 2.6 Gt in 2005, 9.6% of the world total 27.1Gt (IEA, 2007a). Power generation accounted for 1.14 Gt $CO_2e$, or 44% of the total. The remaining GHG emissions split between industry, transportation, and other (residential and commercial) accounting for 35%, 15%, and 9% respectively.

In 2005, average GHG emissions per capita were 1.25 $tCO_2e$/cap, well below the world average of 4.22 $tCO_2e$/cap. For further comparison, the OECD and non-OECD averages were 11.02 and 2.52 $tCO_2e$/cap respectively. This clearly illustrates how low the per capita GHG emissions are in the study region, at half the non-OECD average. For

further perspective, if the study region's per capita emissions were equal to the North American average, global GHG emissions would more than double.[10]

Between 1995 and 2005, GHG emissions per unit of primary energy demand increased by 1% annually, while the world average decreased by 1% annually. Further, $CO_2e$ per GDP only changed by -0.35%, compared to the world average of -14.4% during the same time-period (IEA, 2007a). These results indicate that GHG efficiency gains have been marginal in the study region to date.

## 3.5 Primary Energy Conversion Technologies

Within the CIMS model, conversion technologies turn primary energy into usable forms of final energy (see Table 13 below). Within the electricity generation sector, fossil fuel and nuclear technologies compete for base load, shoulder load, and peak load demands. Renewable technologies are included in this competition mainly for base load, with the exception of large hydro that also competes for peak load demand. Representation of cogeneration technologies that produce electricity and heat is within several of the industry sub-sectors. CIMS also represents technologies for non-electricity energy carriers including oil refineries, natural gas refineries, coal mining, and solar thermal water heating.

$CO_2$ emissions from electricity and heat production are much higher in the study region than other non-OECD regions, at 728 grams $CO_2$/kWh compared to 566 grams $CO_2$/kWh respectively (IEA, 2005). At 29% higher than the OECD average, the study region has one of the highest GHG per units of electricity rates in the world. Another challenge is the level of transmission and distribution losses as a share of total electricity generation. For example, in India the total loss is 32% on average, with losses as high as 50% in some systems compared to the OECD average of 14% (IEA, 2007a).[11] Transmission and distribution losses ultimately result in unpaid electricity generation and losses in revenue. In addition to challenge of losses, many regions charge less for

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[10] Method used to generate estimate: The North American average per capita emission are 15.5 tCO2e/cap. New emission would be equal to 15.5 tCO2e/cap – 1.25 tCO2e/cap * population (2.1 billion) = 29 Gt CO2e.

[11] Figures include own use of electricity in power stations.

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electricity than it costs to produce, as with the State Electricity Boards in India (IEA, 2007a). As a result, regions like India are limited in their ability to invest in less polluting coal technologies.

**Table 13:    Energy conversion technologies in CIMS-Asia**

| Electricity – Renewables | Electricity - Fossil Fuels |
|---|---|
| Hydro dams (large, micro)<br>Wind turbine<br>Solar thermal collectors<br>Solar photovoltaic systems<br>Ground source heat pumps (geothermal)<br>Biomass steam power plant<br>Fuel cell generator | Coal:  Single cycle<br>          Integrated gasification combined cycle<br>          Pulverized fluidized bed<br>          Integrated gasification combined cycle + CCS<br>          Single cycle + CCS<br>Natural Gas:   Single cycle<br>                     Combined cycle<br>                     Combined cycle + CCS |
| **Electricity - Nuclear**<br>Nuclear existing reactor<br>Nuclear Candu reactor | Diesel:          Single cycle<br>Heavy oil:     Single cycle<br>Light oil:       Single cycle |
| **Production of non-electric energy carriers**<br>Oil refinery<br>Natural gas refinery<br>Coal mining<br>Solar thermal water heating | **Cogeneration (electricity & heat)**<br>Industrial cogeneration:   Oil<br>                                     Natural gas<br>                                     Biomass<br>District heat and power:   Natural gas<br>                                     Biomass<br>Waste fuels steam & heat power plant |

Source: adapted from Melton (2008) and Tu (2004)

## 3.6 Carbon Capture and Storage (CCS)

Cost estimates for mitigating $CO_2$ with carbon capture and storage (CCS) vary primarily on the capture technology type and the method of storage (IEA, 2007a). Table 14 provides cost estimates ($US/t$CO_2$ stored) for two types of coal fired power plants and one type of natural gas plant. Natural gas is the most costly of the three options, primarily because there is less carbon to capture from the emissions. Of the two coal technologies, pulverized coal technologies are more costly for both capture and storage due to the sub-critical combustion process. Countries within the study region face challenges at both the technological and the storage option level for CCS. In terms of CCS from coal, the region relies almost solely on sub-critical coal fire technologies with cost estimates of $39 - $115 per tonne $CO_2$, not including transportation. At the storage

level, the region is limited in options for enhanced oil recovery. Estimates for storage potential in the region are 670 Gt $CO_2$ in deep saline aquifers, but only 4.6 Gt $CO_2$ for enhanced oil recovery (Loulou & Labriet, 2004). Due to the current sub-critical coal technology mix, brown coal reserves, and storage options, it would be reasonable to conclude that average costs for CCS would be at the upper end of the $39 - $115 per tonne $CO_2$ range.

**Table 14:    IPCC Cost Estimates for Carbon Capture and Storage (US$/tonne $CO_2$)**

| Mitigation Cost ($US/t$CO_2$ stored) | Power Generation Technology | | |
|---|---|---|---|
| **Storage Option** | Pulverized Coal Power Plant | ICGCC* Power Plant | NGCC** Power Plant |
| Geologic Storage | 30 – 71 | 14 - 53 | 38 – 91 |
| Enhanced Oil Recovery | 9 – 44 | (-7) - 31 | 19 – 68 |
| Total Range | 39 - 115 | 7 - 84 | 57 - 159 |

Source: IEA (2007a) *Integrated Coal Gasification Combined-Cycle **Natural Gas Combined Cycle

Currently there are no CCS facilities in the study region. India and The Republic of Korea are the only two countries actively exploring CCS as an option through information sharing agreements. In 2007, India launched the Indian $CO_2$ Sequestration Applied Research Network to develop a framework for activities and policy studies. India and The Republic of Korea are also members of the Asia Pacific Partnership on Clean Development and Climate, an agreement intended to promote technology deployment and transfer (APPCDC, 2007). However, India has adopted a reserved position on investing in CCS and near zero fossil-fuel plants due to high costs and technical uncertainties (IEA, 2007a).

# CHAPTER 4: SIMULATION RESULTS

In the previous chapter, energy system information from 2005 set the context for the model forecasts presented in this chapter. Section 4.1 begins with a discussion of the methods used to calibrate CIMS-Asia in the reference run. Next, Section 4.2 provides the results of the reference run from 2005 to 2050, setting a baseline for comparing the policy run results. With a baseline established, Section 4.3 presents the results from the policy runs. Finally, Section 4.4 tests some of the key assumptions made in generating the results of this study with a sensitivity analysis, including the exogenous stock forecast and availability of widespread CCS.

## 4.1 Calibration of the Reference Run

To improve the accuracy of the reference run, it was necessary to calibrate CIMS-Asia with 2005 data provided by the International Energy Agency (IEA) and the U.S. Energy Information Administration (EIA). Calibration was necessary because (1) data were lacking for some sectors and (2) it increases the confidence in the modelling results. As the CIMS model generates forecasts in five-year time intervals, 2005 is the most recent year for comparison to historic data. The calibration method was to match energy consumption in each major sector to within 5% of 2005 data (adapted from Tu, 2004). Table 14 illustrates that for 2005, all sectors are within the 5%, with total energy consumption being within 0.2% of historic data. Only minor adjustments to the residential, commercial, and some industry sub-sectors were required so that energy consumption results were within 5% of 2005 data. As mentioned in the previous chapter, data limitations were primarily in these sectors.

**Table 15: Calibration of the reference run (2005), and comparison with forecasts (2030)**

| Units: EJ | 2005 - Calibrated | | | 2030 - Comparison | | |
|---|---|---|---|---|---|---|
| | IEA/EIA* | CIMS | %Difference | IEA/(EIA)* | CIMS | %Difference |
| Residential | 3.8* | 3.8 | 0.0 | 7.3* | 7.3 | 0.0 |
| Commercial | 1.5* | 1.5 | 0.0 | 3.9* | 3.9 | 0.0 |
| Industry | 12.3 | 12.0 | -2.5 | 23.0 | 24.1 | 4.6 |
| Transport | 6.7 | 6.7 | 0.0 | 13.7 | 14.0 | 2.1 |
| Total | 24.6 | 24.1 | -2.1 | 51.1 | 49.3 | -3.6 |

Note: EIA data were used for residential and commercial data because the IEA aggregates these sectors into a single sector. For this reason, the total does not exactly match the sum of the sectors.

Source: IEA Non-OECD Energy Balances (2008a), IEA World Energy Outlook (2006a), *EIA International Energy Outlook (2007)

Beyond 2005, a comparison of CIMS-Asia forecasts with those of other modelling groups served two primary purposes. First, the comparison help to catch any mistakes that may have occurred while developing and applying CIMS-Asia. Second, it establishes a certain degree of model credibility. The reason for not calibrating CIMS-Asia to other forecasts is that it would conflict with the goal of creating a unique set of forecasts by applying a different methodology. Instead, forecasts made by the IEA and EIA to 2030 provided a basis for comparison. Table 15 indicates that results from CIMS-Asia also fall within 5% of the forecast made by the IEA for total final consumption in 2030.

For total GHG emissions, CIMS-Asia forecasts are 1.2% higher in 2005 compared to historic data, and 7.2% higher than forecasts made by the IEA for 2030 (see table 16). These results differ from those for total final consumption above, where CIMS is forecasting slightly lower than the IEA.

**Table 16: CIMS-Asia and IEA GHG emissions forecast comparison**

| Units: Gt $CO_2e$ | 2005 | | | 2030 | | |
|---|---|---|---|---|---|---|
| | IEA | CIMS | %Difference | IEA | CIMS | %Difference |
| Total | 2.44 | 2.47 | 1.2 | 5.02 | 5.38 | 7.2 |

## 4.2 Results of the Reference Run Forecast

In this section, presenting the results from the reference run illustrates the expectation of what will occur in the absence of significant climate policy in the study region. After exploring the reference run to establish a baseline for comparison, the section following will focus on the policy run results.

### 4.2.1 Energy Consumption

Between 1990 and 2005, total primary energy demand in the study region increased at an annual rate of 3.8%, reaching 40.6 EJ by 2005. Reference run results from CIMS-Asia suggest that total primary energy demand will increase by 3.0% per year from 2005 to 2030, and then slow to 1.9% per year from 2030 to 2050. At these growth rates, primary energy demand reaches 112 EJ by 2050 (Figure 7 below). Between 2005 and 2050, the study region's share of global primary energy demand increases from 8.5% to 14%.[12] Given these estimates, the study region will account for roughly 19% of the global increase in primary energy demand between 2005 and 2050.
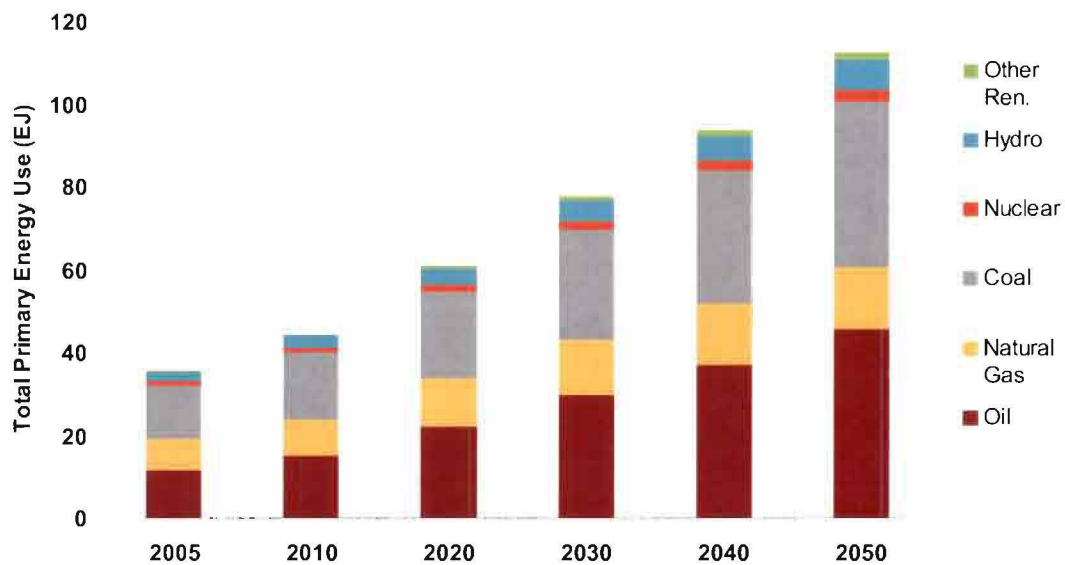


**Figure 7:    CIMS-Asia forecast for total primary energy demand, by fuel type**

[12] Based on 471 EJ of primary energy demanded in 2005 (IEA, 2006) and POLES forecast of 898 EJ for world primary energy demand in 2050(EC, 2006)

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Figure 7 illustrates the forecast for growth in each primary form of energy consumption over the modelling period. GHG intensive fossil fuels maintain a relatively constant share of fuel mix at roughly 95% to 2050. The only noticeable trend is a decrease in natural gas demand, offset by an increase in oil demand. Nuclear, hydropower, and other renewables represent the other 10% of primary energy demand over the modelling period. Within the low carbon fuel mix, the only noticeable trend is a small relative decrease in hydropower shares, made up for by a slight increase in other renewables (wind/solar/biomass). Nuclear maintains a relatively constant share of the fuel mix over the modelling period. For both hydro and nuclear, maximum market shares were set to reflect physical and political limits.

The demand for primary energy illustrated in Figure 7, is largely driven by final consumption of energy within each of the major end-use sectors in the energy system. Figure 8, provides the forecast for total final consumption (end-use demand) over the modelling period, disaggregated by sector.
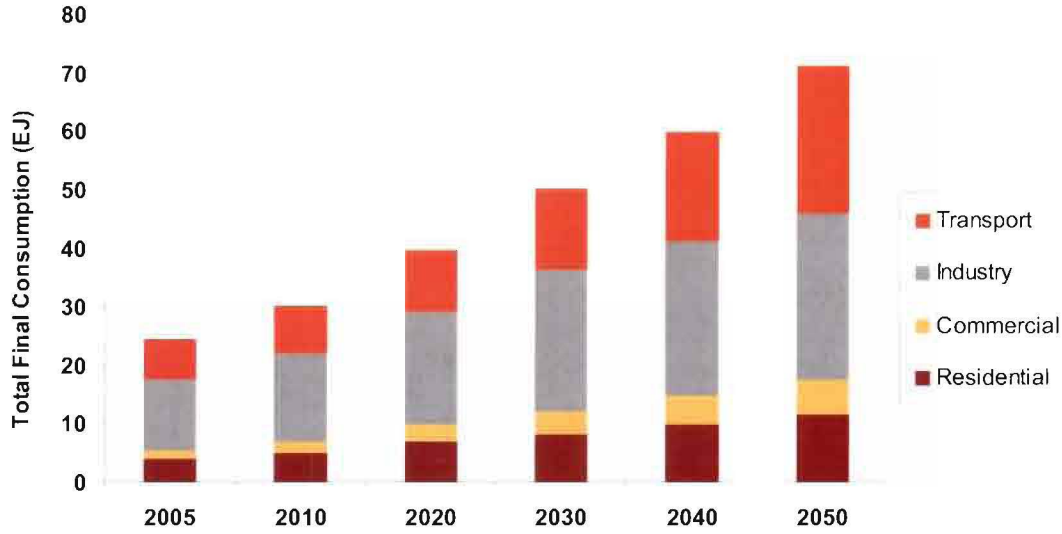


**Figure 8:    CIMS-Asia forecast for total final consumption, by sector in the study region, by sector**

Industry represents roughly 50% of total final consumption from 2005 to 2030, but then decreases to 40% between 2030 and 2050. The average annual growth rate for industry from 2005 to 2050 is 1.9%, the lowest of all four sectors. The transportation sector maintains a 28% share to 2030, and then increases to 36% by 2050 filling most of the share lost by industry. These results are consistent with forecasted growth rates for each sector that suggest industry growth will slow to roughly 3% by 2030, while transportation maintains a higher 4% growth (IEA, 2007a). Averaged over the entire modelling period, the annual growth rate of the transportation sector is 3.0%. CIMS-Asia estimates that the residential sector will maintain a relatively even share of end-use demand, at roughly 16% during the entire modelling period. End-use energy demand in the commercial sector grows at 3.1% on average per year, as the relative share increases from 6% to 9% between 2005 and 2050.

### 4.2.2 GHG Emissions

Over the modelling period GHG emissions increase at a rate of 2.5% per year on average, compared to the global average of roughly 1.2% (EC, 2006). GHG emissions increase from 2.5 Gt $CO_2e$ in 2005 to 7.7 Gt $CO_2e$ in 2050, a 300% increase. By 2050, forecasts indicate the study region will represent 17% of global emissions, slightly higher than its 14% share of global demand for primary energy[13]. The difference indicates that the study region has a higher GHG to primary energy demand ratio than the global average. Industry remains the predominant source of GHG emissions from 2005 to 2050, decreasing slightly to 50% by 2050. By 2050, transportation accounts for 27% of GHG emissions, with the remaining emissions split between residential and commercial (see figure 9).

The commercial sector is the only sector with significantly different average annual growth rate in GHG emissions than end-use energy demand, at 3.7% versus 3.1% respectively. This suggests the commercial sector will become more GHG intensive over the modelling period, in contrast to the other sectors. Within the three other sectors growth in end-use energy demand compared to GHG emissions are relatively consistent.

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[13] POLES forecasts to 2050 are used for these comparisons (EC, 2005)
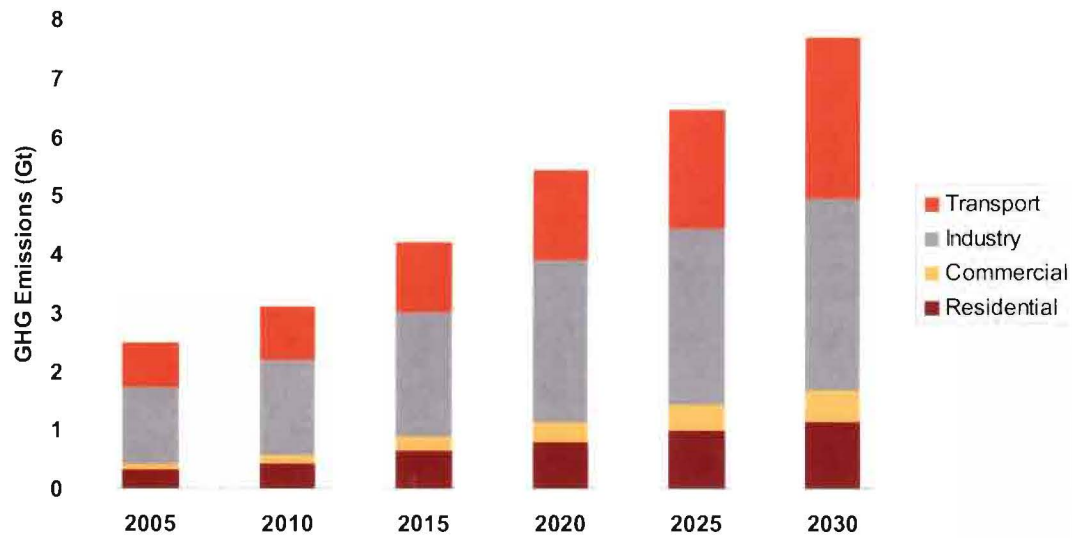
**Figure 9:    CIMS-Asia forecast for GHG emissions, by sector (Gt)**

### 4.2.3 Electricity Generation

Electricity generation represents 48% of total primary energy demand in the study region.  Figure 10 disaggregates electricity generation from different primary fuel sources over the modelling period.  CIMS-Asia forecasts that fossil fuels will dominate the primary energy supply for the electricity sector, increasing from 81% to 82% over the modelling period.  Coal maintains a relatively constant share of the fuel mix, at roughly 60% over the modelling period.  The relative share of gas decreases slightly, as oil shares increase to make up the difference.  Overall, renewable energy sources maintain a constant 12% share to 2050, with hydropower decreasing slightly due to physical resource limitations. Wind, solar, and geothermal make up the difference with a slight increase in share over the same period.  Wind power is responsible for the majority of this increase, but like hydro, has physical limitations.  In total, the fuel mix in the electricity sector becomes slightly more GHG intensive over the modelling period.
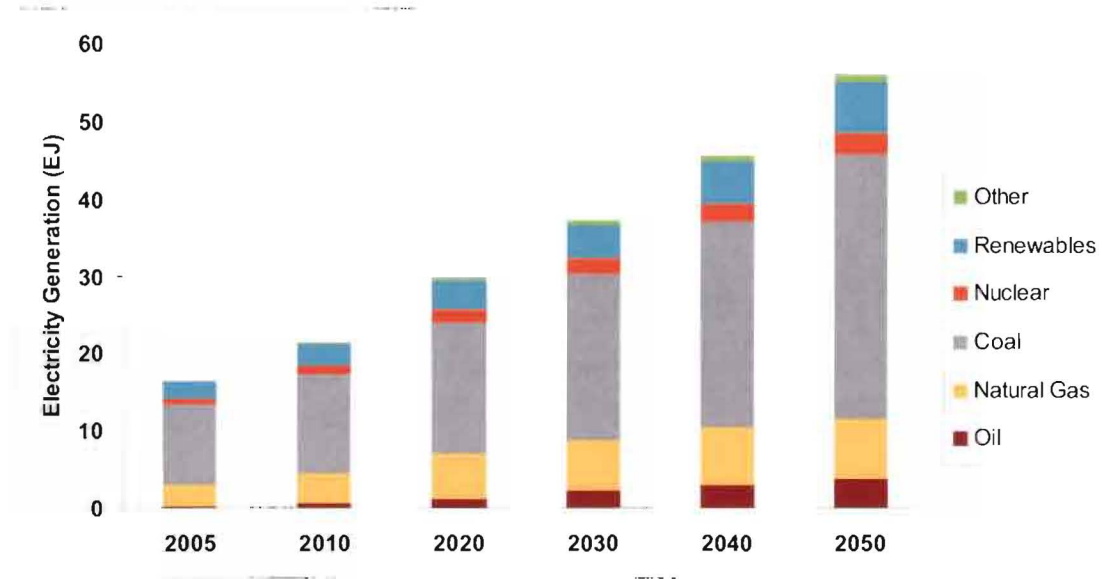
**Figure 10:** Electricity generation from different fuel sources (EJ)

### 4.2.4 Intensity Trends

Intensities trends are a valuable method of tracking the relative changes within an energy system. Presented here are estimates for GHG and energy intensity over the modelling period. In addition, the intensity trends of the Japan/Pacific provide a comparison with a more developed energy system. Table 17 indicates that GHG intensity/energy consumption ($tCO_2e/tce$) of the study region remains relatively constant to 2050. This is consistent with forecasts for the fuel mix over the modelling period, suggesting a shift towards more GHG intensive fuels. In contrast, the same energy intensity in the Japan/Pacific region decreases by roughly 25% (EC, 2006). Energy intensity per unit of GDP (Kgce/$US) decreases by 44% over the modelling period, compared to a 55% decrease in Japan/Pacific. As well, GHG intensity per unit of GDP (KgCO2e/$US) decreases by 67% over the modelling period.

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**Table 17: CIMS-Asia forecasted energy and GHG intensities**

|  | 2005 | 2010 | 2020 | 2030 | 2050 |
|---|---|---|---|---|---|
| Per capita GHG emissions ($tCO_2e$/capita) | 1.2 | 1.4 | 1.7 | 2.0 | 2.6 |
| Energy intensity per GDP (Kgce/US$, 2005 price) | 0.5 | 0.4 | 0.4 | 0.3 | 0.3 |
| GHG intensity/energy consumption ($tCO_2e$/tce) | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 |
| GHG intensity/GDP ($KgCO_2e$/US$, 2005 price) | 0.3 | 0.3 | 0.2 | 0.2 | 0.1 |

These results suggest the economy will become gradually less energy and GHG intensive to 2050. Per capita $CO_2e$ emissions increase rapidly, more than doubling by 2050. In 2050, CIMS-Asia forecasts per capita GHG emissions to be 2.6 $tCO_2e$/cap, compared to the POLES forecast of 5.0 $tCO_2e$/cap for the world average (EC, 2006).

# 4.3 Results of the GHG Abatement Forecasts

The previous section presented the reference run results of the CIMS-Asia model, creating a baseline for comparing the GHG mitigation runs presented next. In the following section, results illustrate the outcome of applying a charge on $CO_2e$ within the CIMS-Asia model. The accuracy of GHG emissions abatement forecasts is dependent on the accuracy of both the BAU forecast and the ability of CIMS to estimate the response of the energy system to emissions charges. Given how fallible models are at accurately predicting the future in absolute terms, it is preferable to view the following results in relative terms. That is, the value of the information is in the relative magnitude and direction of change versus the absolute change.

### 4.3.1 Marginal Abatement Cost Curves

Marginal abatement cost curves are useful for illustrating the cost of GHG emissions abatement. The charge on GHG emissions represents the maximum charge needed to achieve a given level of emissions reduction (Criqui et al., 1999). In figure 11, the y-axis represents the maximum charge ($/$tCO_2e$) that is forecasted to achieve a given reduction in emissions ($MtCO_2e$) on the x-axis. Figure 11, represents an estimate of the amount of emissions available for reduction from three emissions price paths starting from $0/tonne $CO_2e$ in 2010 and increasing linearly to $200/tonne $CO_2e$ in 2030, 2040 and 2050.

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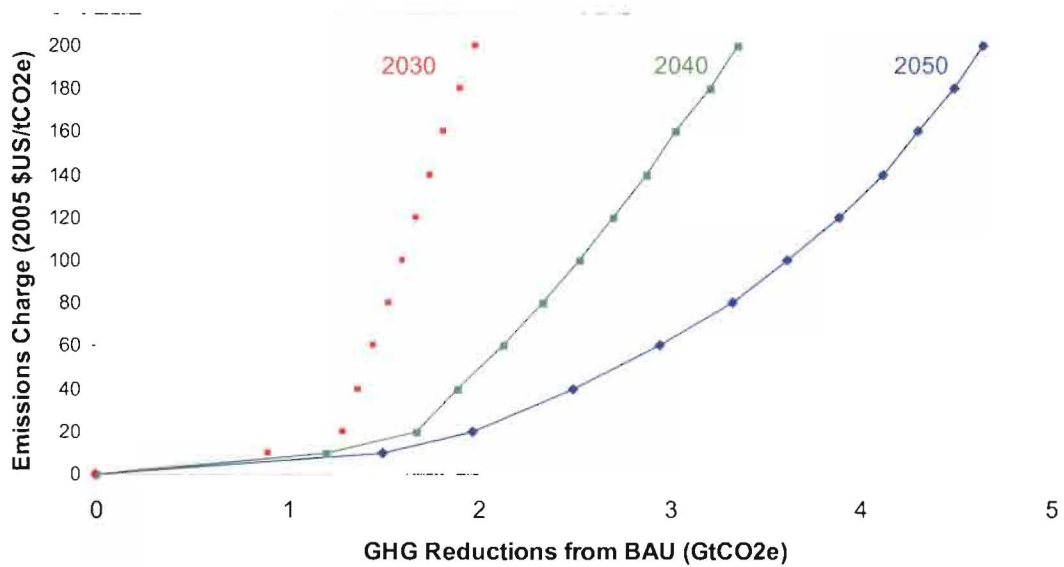
**Figure 11:  Marginal abatement cost curves generated by CIMS-Asia**

Three curves illustrate that the amount of emissions available for reduction is largely a function of (1) the magnitude of the charge and (2) the amount of time that a charge is applied.  The latter suggests that delaying action to reduce GHG emissions requires higher missions charges to achieve the same reductions at a given date in the future.  For example, at $40 tonne $CO_2e$ the number of emissions abated is roughly double in 2050, compared to 2030.  The increased emissions abatement in 2050 relates to the timing of capital stock turnover.  By 2030, consumers and firms have only had 15 years to adjust to the increased costs, with some capital stocks having lifetimes of 30 years.  In contrast, by 2050 the replacement of all capital stocks has occurred with the added cost of GHG emissions included in the technology selection process.

The upward sloping curves are representative of the law of diminishing marginal returns, where added output ($CO_2e$ abatement) from successive increases in effort eventually diminishes (Ward, 2006).  As an example, consider the increasing costs of achieving near-zero GHG emissions in an electricity sector.  At first, there are several relatively low costs methods of reducing emissions, such as improving power plant

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efficiencies. However, moving towards near-zero GHG emissions would require increasing investments in new technologies such as widespread carbon capture and storage.

### 4.3.2 Sectoral Marginal Abatement Cost Curves

The previous section presented MAC curves for the entire energy system of the study region. In this section, a presentation of sectoral MAC curves highlights variation in abatement potential among the demand sectors. As above, the results are from emissions charges starting in 2011 and increasing linearly to 2050. In terms of absolute reductions in 2050, Figure 12 provides estimates generated by CIMS-Asia for the industry, commercial, residential, and transportation sectors.
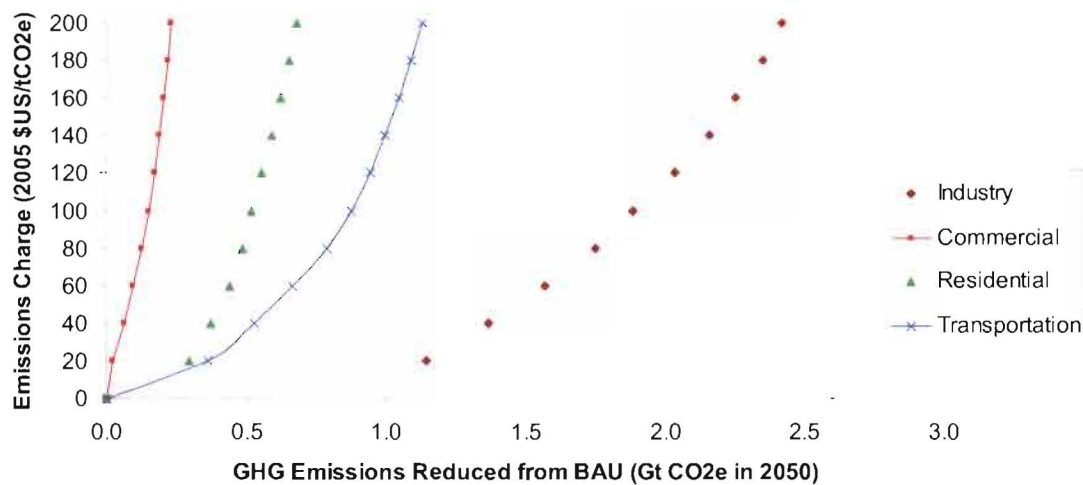


**Figure 12:  Sectoral marginal abatement cost curves generated by CIMS-Asia (GtCO$_2$e)**

Emissions associated with electricity generation are included in these curves, based on sector demand for electricity. Clearly, the industry sector provides the most opportunity for emissions reduction of the four sectors. With an emissions charge of $100/tonne CO$_2$e, a total reduction of 1.9 Gt occurs within the industry sector, compared to roughly 1.5 Gt from all of the other sectors combined. These results are consistent

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with the absolute amount of emissions generated by each sector over the modelling period in the BAU.

To investigate the relative ability of individual sectors to reduce GHG emissions below the BAU, Figure 13 illustrates the relative MAC curves for each sector in 2050. In terms of relative reductions, the sectors appear to respond similarly to an emissions charge in terms of the shape of each curve. The only significant difference in relative reduction is within the residential sector, which results in relatively fewer emissions reduced than the other sectors on a percentage basis.
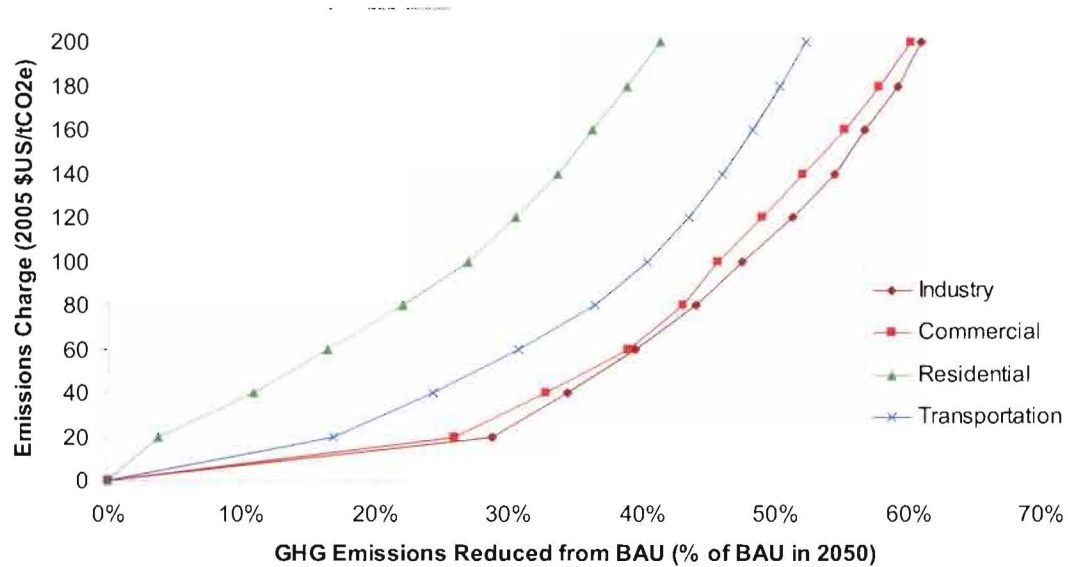


**Figure 13: Sectoral marginal abatement cost curves generated by CIMS-Asia (%)**

The results from Figure 12 and 13 indicate that the industry sector provides the greatest opportunity for emissions reduction, both in absolute and relative terms. For example at US $100 per tonne, industry accounts for roughly 55% of total reduction in GHG emissions. Together, the transportation and industrial sectors account for roughly 75% of emissions reduction at US $100 per tonne.

### 4.3.3 GHG Emissions Price Pathways

An "emissions price pathway" represents a series of charges placed on GHG emissions over time, preferably starting low and increasing over time. As CIMS-Asia is a newly developed tool for analysis of climate policy, the simulation of emissions charges served several purposes for this study. First, it provided information needed to address the specific research questions of this study. Second, it allowed for the generation of comparable results with other studies to highlight methodological differences. The following are the three emissions price paths simulated in CIMS-Asia.

*Contraction and Convergence:* The contraction and convergence (C&C) policy architecture was developed as an equitable approach to global emissions reduction, based on a global per capita emissions target. Under this scheme, countries begin by "contracting" their emissions, and then begin "converging" on a global per capita emissions target (Böhringer & Welsch, 2004). For this study, the target was set to per capita emission of 1.89 tonnes $CO_2e$ by the year 2050.[14] Several iterations of linearly increasing $CO_2e$ emissions charges resulted in an emission price pathway of \$3/tonne $CO_2e$ in 2015 increasing to \$27/tonne $CO_2e$ by 2050 meeting the target.

*Bataille et al :* In Bataille et al. (2008), the authors use regional CIMS models to simulate an emissions charge in Canada and China, starting at \$10 a tonne $CO_2e$ in 2013 and increasing exponentially to \$100 a tonne $CO_2e$ in 2050. This emissions price pathway resulted in a 48% reduction from BAU emissions within the study region by 2050. The emissions trajectory indicates that GHG emissions have stabilized at roughly 4.4 Gt per year by 2050.

*Stabilize Emissions:* As previously mentioned, it was not possible to achieve emissions reduction of 50% below 2005 levels by 2050 without exceeding an emissions charge of \$400 a tonne $CO_2e$ in 2050. Emissions charges of this magnitude are very unlikely for

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[14] Target is based on reaching a global emissions level of 13.6 Gt/year by 2050, a figure suggested by Weaver et al. (2008) that would avoid causing a 2 degree Celsius increase in global temperatures within this century.

the developing economies of the study region. As a compromise, stabilizing emission at 2010 emission levels by 2050 served as a strict emissions target. To stabilize emissions to 2010 levels, an emissions charge of $31/tonne $CO_2$e was necessary in 2015, increasing linearly to $250/tonne $CO_2$e by 2050. This emissions price pathway resulted in a 64% reduction from BAU emissions within the study region by 2050. The emissions trajectory indicates that GHG emissions have also stabilized, but at a lower annual rate of 3.0 Gt per year by 2050. To achieve the additional 14% reduction in BAU emissions in 2050 requires an emissions charge 2.5 times higher. These findings are consistent with the MAC curves shown above, where emissions abatement above 50% relative to the BAU requires an exponential increase in emissions charge. Figure 14 provides the results of the three emissions price paths, in contrast to the business as usual forecast. The emissions trajectories correspond to the emissions charges in the table directly below.



| Policy price pathways: Tax (2005 $US/tCO₂e) below corresponds to emissions pathway above | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2000 | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
| Contraction & Convergence | | 0 | 3 | 4 | 5 | 7 | 10 | 14 | 20 | 27 |
| Bataille et al. | | 0 | 10 | 14 | 19 | 27 | 37 | 52 | 72 | 100 |
| Stabilize to 2010 Emissions | | 0 | 31 | 63 | 94 | 125 | 156 | 188 | 219 | 250 |
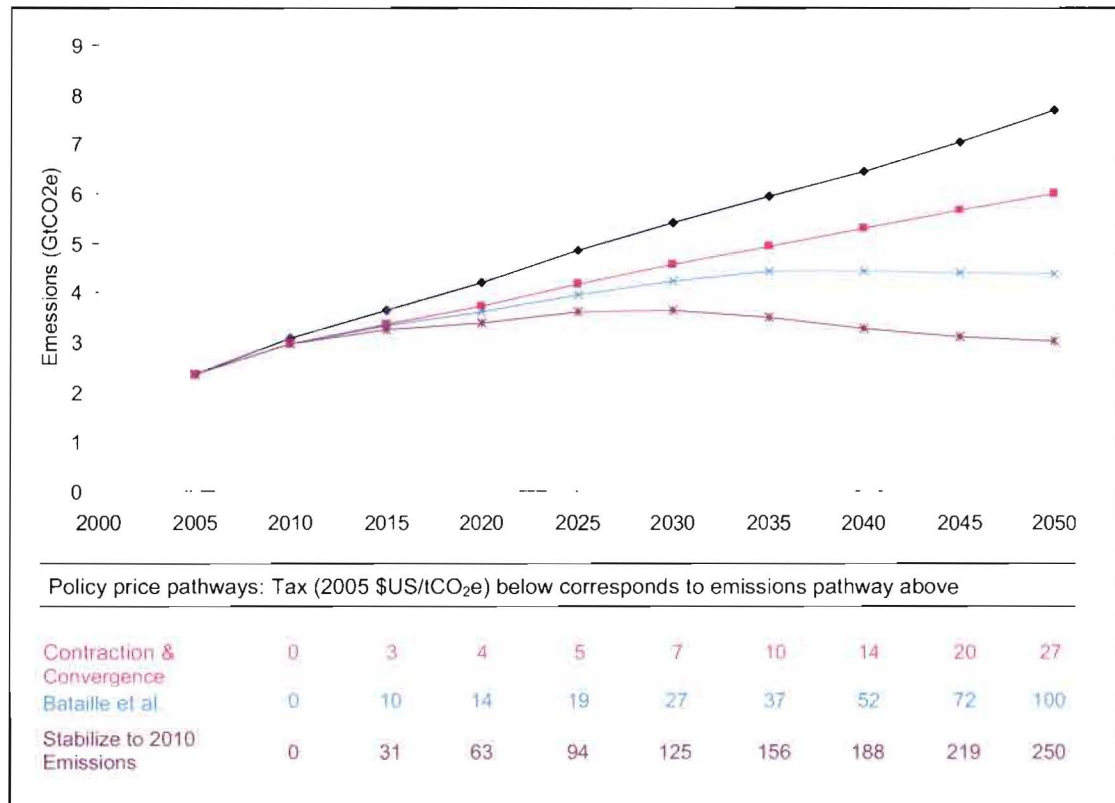
**Figure 14: Policy price pathways with resulting reductions in emissions compared to the business as usual case.**

A significant portion of the GHG emissions reductions in these results are from carbon capture and storage (CCS), accounting for over 60% by 2050. For this reason, a sensitivity analysis on the availability of CCS follows in Section 4.5. Fuel switching resulted in roughly 17% of emissions reductions, being reductions from switching to less GHG intensive fuels, such as coal to natural gas or nuclear. Energy efficiency improvements additional to those expected in the BAU resulted in approximately 6% of emissions reduction. Finally, roughly 16% of reductions occur from changes in physical output, as GHG intensive products become more expensive to manufacture and purchase.

### 4.3.4 The Cost of Emissions Abatement Policy

CIMS estimates the impact of a policy on gross domestic product (GDP) by calculating the direct effects on sectoral output resulting from the policy. For example, this would be GDP reduction caused by a decrease in cement production, resulting from increased costs associated with an emissions charge. Figure 15 illustrates the reduction in the region's total GDP resulting from the CIMS response in each sector to an emissions charge.
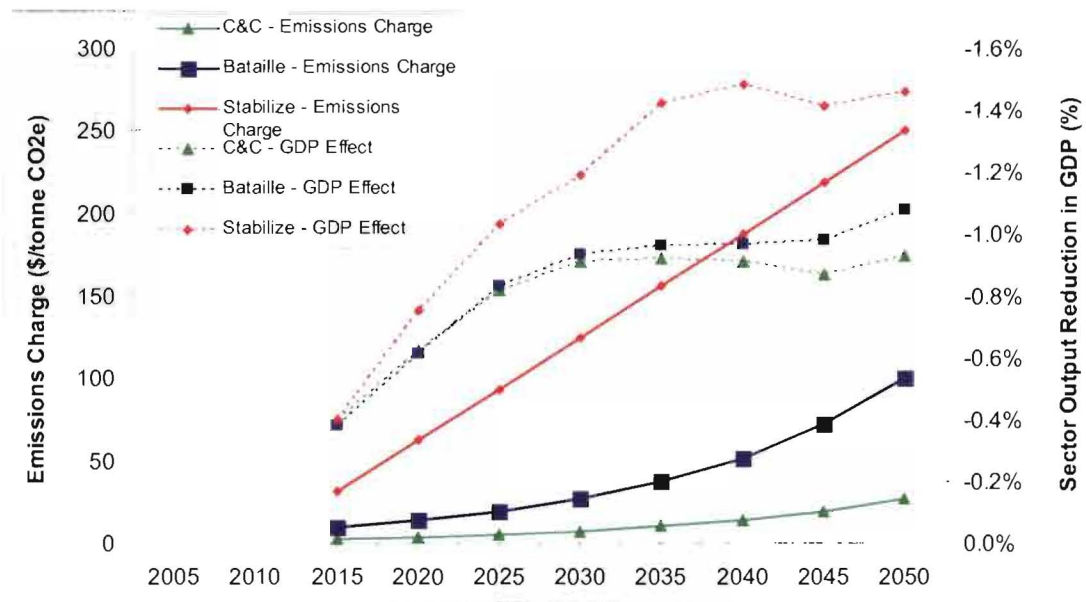


**Figure 15:** **Policy effect on sector output in terms of total reduction in GDP**

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Since CIMS does not reach full equilibrium, accounting for secondary effects of emissions charges is not possible. For this reason, the GDP effects reported by CIMS are sector specific as apposed to covering the entire economy. As expected, there is a clear trend between an increasing emissions charge and an increased reduction in GDP. The relationship is not linear, as the reduction in GDP begins to plateau between 2030 and 2035, even as the emissions charge continues to increase. An explanation for these results could be that the reduced effect on GPD is a result of capital stock turnovers. The reduction in GDP begins to plateau after 15 to 20 years, providing incentives for the selection of less GHG intensive goods and services as capital stocks were retired and replaced.

## 4.5 Sensitivity Analysis

Generating the results of this study required numerous assumptions about the energy system of the study region. An important consideration is how significant each assumption is in terms of influencing the results. A sensitivity analysis is a method of testing these assumptions, by examining the sensitivity of the results to varying a single parameter or combination of parameters, with all else held constant. In the development of CIMS-China, Tu (2004) tested the assumptions made about fuel prices, discount rates, and the variance parameter. The findings were that the results were not significantly sensitive to changes in parameters within an expected range of possibilities. Given the similarities of CIMS-China and CIMS-Asia, it is felt that little will be learned form performing the same sensitivity analysis. Instead, the assumptions of this study were reviewed keeping two factors in mind – uncertainty and significance. Under this lens, it is felt that the assumptions most in need of a sensitivity analysis are the exogenous stock forecast and timing of the widespread availability of carbon capture and storage.

### 4.5.1 Macroeconomic Growth Forecast

The macroeconomic forecast represents the expected demand of services and energy intensive goods from each sector or sub-sector. As discussed earlier (section 2.1.1), the model user must set this forecast for the entire modelling period in order to initiate the CIMS model sequence. For example, the commercial sector requires the total

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amount of floor space demanded over the modelling period. The macroeconomic forecast is set in the model to guide the iterations that occur between demand and supply models. This forecast creates a guide for the model, and should have a significant influence on the BAU forecast. What is of particular interest is how changes in the macroeconomic forecast will affect the abatement costs. As previously discussed, it was necessary to extrapolate the macroeconomic forecast beyond 2030 due to a lack of data. It is also important to note that although data to 2030 is from reputable sources, all forecasts are uncertain. For example, the IEA updates its forecast to 2030 every year in the World Energy Outlook (WEO) in light of new information. Between 2006 and 2007, the IEA's forecast for global primary energy demand increased by 5% (IEA, 2006a & 2007a).

Table 18 provides the results from a sensitivity analysis on the macroeconomic forecast for each major sector, and the resulting changes in BAU forecasts to 2050. The method was to create a range of conceivable stock forecasts using the high and low growth rates from the IEA. China and the European Union had the highest and lowest average annual growth rates in energy demand to 2030 at 3.5% and 0.5% respectively (IEA, 2006a). The forecasted average annual growth rate in macroeconomic forecast for the study region is 2.2% over the modelling period. The method applied was to use the base year data for 2005, and extrapolate it under low (0.5%) and high (3.5%) growth rates. The result was stock forecasts being 45% lower and 89% higher than the current forecasts in 2050.

**Table 18: Sensitivity analysis of exogenous stock forecast effect on BAU results**

| | Stock Forecast Decrease in 2050 | Decrease Energy Consumption Results | Decreases GHG Emissions Results | Stock Forecast Increase in 2050 | Increases Energy Consumption Results | Increases GHG Emissions Results |
|---|---|---|---|---|---|---|
| Residential | -45% | -43% | -43% | 89% | 81% | 80% |
| Commercial | -45% | -45% | -45% | 89% | 88% | 86% |
| Industry | -45% | -45% | -45% | 89% | 88% | 88% |
| Transport | -45% | -45% | -46% | 89% | 89% | 89% |
| Electricity Generation | -45% | -45% | -47% | 89% | 89% | 95% |
| Total | -45% | -45% | -46% | 89% | 88% | 90% |

The high and low stock forecasts were then simulated in CIMS-Asia to determine the effect on energy consumption and GHG emissions. The sensitivity analysis clearly demonstrates that the BAU results of CIMS-Asia are very sensitive to the macroeconomic forecast. What these results indicate is that the accuracy of the reference run results from CIMS-Asia are highly dependant on the accuracy of the exogenous stock forecast. With the effect on the BAU understood, consideration will now be given to how changes in the macroeconomic forecast affect the results of the policy runs. Figure 16 provides a comparison of relative MAC curves generated by using the same growth rates as discussed above.
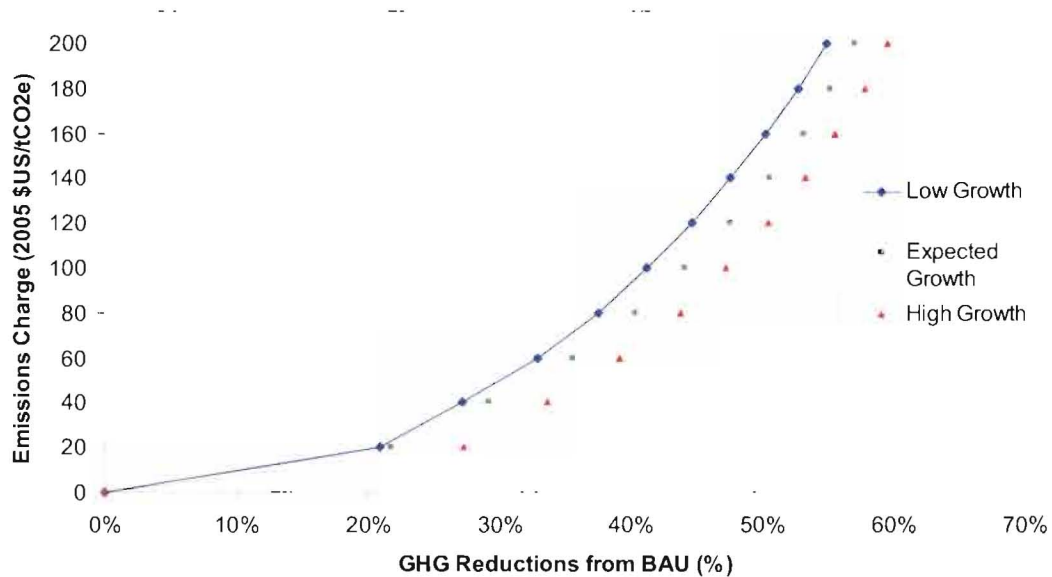


**Figure 16: MAC curves for various exogenous stock forecast growth rates**

The method applied for testing this effect was to compare the relative marginal abatement costs (MAC) curves generated with the low and high macroeconomic forecast growth rates. These results indicate that large variations in macroeconomic forecasts have little effect on relative emissions reductions. For emissions charges up to US $200/tonne $CO_2e$ in 2050, relative emissions reductions compared to the BAU vary by no more that 4% between the three growth rates.

### 4.5.2 Carbon Capture and Storage

Large-scale implementation of carbon capture and storage (CCS) of $CO_2$ is still in the commercialization phase. Most projects capture and store $CO_2$ primarily for enhanced oil recovery, with only two projects worldwide capturing and storing $CO_2$ because of an emissions charge (IEA, 2007a).[15] However, the International Energy Agency suggests that the adoption of CCS may be widespread if policies are introduced that place a high enough charge on $CO_2$e emissions. As discussed in section 3.6, the study region faces challenges in terms of storage options and the current coal technology mix in the electricity sector. Both of these factors lead to estimates of higher capital cost requirements for the application of CCS in the study region.

These challenges, coupled with CCS still being in the early stages of technological development, indicate that the timing of widespread availability in the study region is uncertain. Figure 17 (below) provide the results of a sensitivity analysis done on the widespread availability of CCS technologies within CIMS-Asia. The results indicate that the timing of widespread CCS availability does have a significant effect on emissions reductions in the study region.

Delaying availability to 2025 resulted in a 52% reduction in relative emissions abatement at a charge of $200/t$CO_2$e, compared to 59% when available immediately. These results suggest that delaying CCS availability for roughly 15 years only decreases emissions reduction by 7% in 2050 relative to the BAU, at $200/t$CO_2$e. When CCS is unavailable over the entire modelling period, results suggest the amount of emissions reduced in 2050 decreases to 35% from 59% relative to the BAU, at $200/t$CO_2$e. Although an unlikely scenario under such a high price on emissions, it illustrates the importance of CCS in reducing abatement costs over the modelling period.

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[15] Both projects are in Norway, resulting from an emissions charge applied to final large emitters of $CO_2$e.
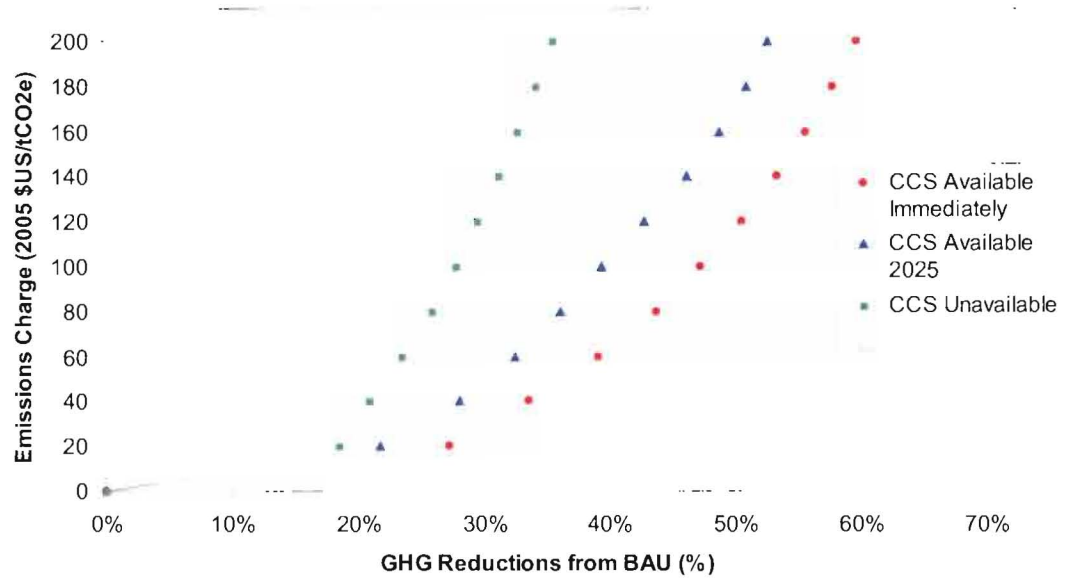
Figure 17: MAC curves for various availability dates of CCS

# CHAPTER 5: DISCUSSION

The goal of the previous chapter was to present the key modelling results from the BAU and several emission abatement runs. This chapter will involve a critical analysis of these results to address the research questions of this study. Where necessary, the results from other studies are used for comparison. In Section 5.1, the discussion focuses on the BAU forecasts to 2050. Section 5.2 provides the abatement costs associated with GHG emissions charges and provides a comparison of the results from four regional CIMS models. In Section 5.3, the methods of the IEA's "Alternative Policy Scenario" are critically assessed, with recommendation made for a better approach. Finally, Section 5.4 concludes with a discussion of the significance of the study results in terms of GHG mitigation policies.

## 5.1 Energy System in the Reference Run

During the modelling project, a significant amount of effort went into developing the BAU forecast for the study region. An accurate BAU forecast provides critical information about the evolution of an energy system, and sets the baseline for the accuracy of the policy runs. If the end goal is to provide useful information for decision makers, a BAU forecast will improve the ability of the model to estimate the effects of policies.

As noted in section 4.1, CIMS-Asia falls within 5% of historic data reported by the IEA in 2005. Figure 18 (below) illustrates that the modelling forecasts of CIMS-Asia to 2030 also closely match forecasts made by the IEA, but differ slightly from those of the Energy Information Administration (EIA). The matching results of the IEA are expected, as the majority of the data used to populate CIMS-Asia was provided by that agency. The difference between CIMS-Asia and the EIA is a result of a slight variation in regional definition, with the EIA including 36 countries versus 31 in CIMS-Asia.
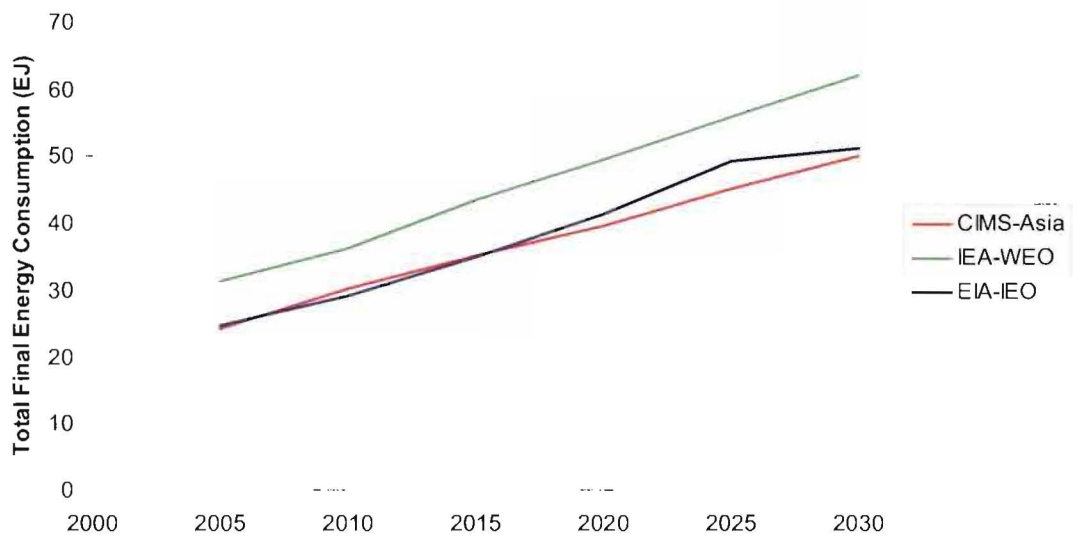
**Figure 18: Comparison of baseline total final energy consumption forecasts for the study region to 2030, by CIMS-Asia, the IEA, and the EIA.**

Source: IEA (2007a), EIA (2007)

To create a basis for comparison to 2050, figure 19 presents $CO_2e$ emissions projections from CIMS-Asia compared to the Special Report on Emissions Scenarios (SRES) made by the International Panel on Climate Change (IPCC, 2001). These results suggest that $CO_2e$ forecasts of CIMS-Asia fall within the mid range of what the IPCC estimates as possible emissions scenarios to 2050. However, there is a significant difference between simulation type forecasts, done in this study, and scenario based forecasts. The goal of simulation based modelling is to generate a single BAU forecast that reflects the best estimate of how the energy system and subsequent GHG emissions will evolve over time. Chapter 2 provides an example of the methodology applied in simulation based modelling, with considerable efforts focusing on the creation of a single accurate reference forecast.
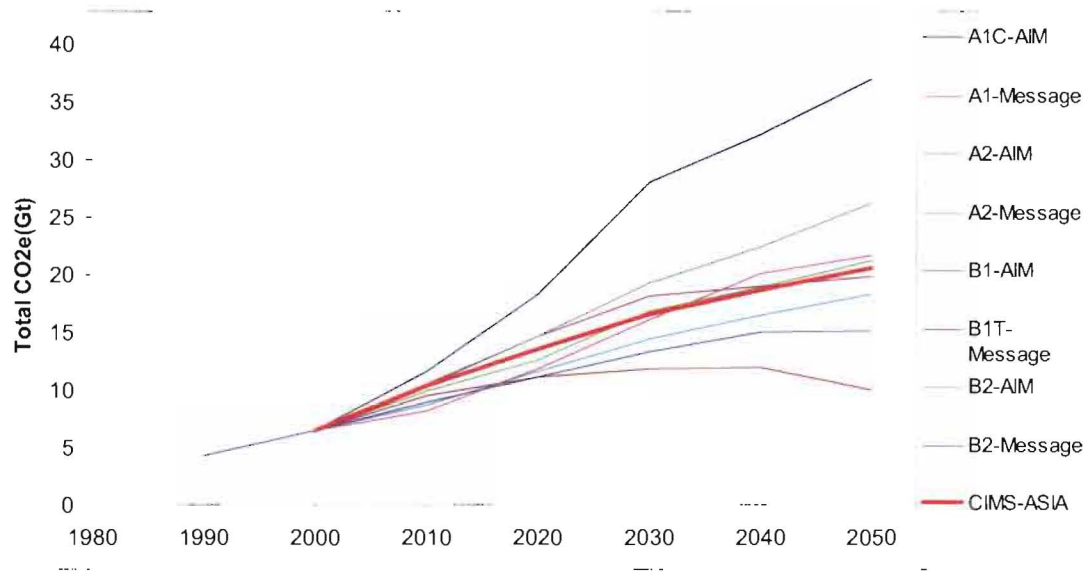
**Figure 19:    CIMS-Asia and the IPCC SRES emission scenarios**
Source: IPCC (2001)

Scenario based modelling such as SRES involves generating a wide variety of
conceivable future outcomes based on varying key modelling parameters.  The scenarios,
known as "storylines", involved adjusting exogenous assumptions such as population
growth, economic growth, environmental protectionism, and political regionalism over
all conceivable future outcomes (Nakicenovic & Swart, 2000).  As an example, the
changes made during the sensitivity analysis for this study are potential future scenarios.
One of the key limitations of this approach is that the conventional wisdom of learning
from the past may be discarded.  For example, Tol et al (2005) finds several false
assumptions about demographics and economic outcomes made in generating the SRES.
An example is that there has not been a global convergence of absolute per capita
incomes, as assumed in all SRES scenarios.

Overall, scenario based modelling runs the risk of providing misleading
information about the likely emissions path of an energy system.  A significant risk is that
scenario based modelling may either confuse decision makers, or worse, provide

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justification for inaction. Consider the different outcome of the results of this study had it involved a scenario based approach and the influence this may have on decision makers faced with the challenges of creating domestic policies that may effect economic growth. For example, if the results from the sensitivity analysis on growth rates were scenarios, the low growth projections could provide justification for inaction.

The following discussion summarizes the significant findings of the BAU forecast. For policy makers, there is an obvious value in understanding how an energy system is likely to evolve in the absence of policy intervention. At the level of international climate agreements, the BAU can inform decision makers about future reductions needed to reach binding targets. The BAU also provides valuable information for domestic policy, including what sectors to target. The following are some of the significant findings of the reference run that may be of value to decision makers.

First, the reference scenario clearly indicates the growing significance of the region in terms of energy demand and global GHG emissions. CIMS-Asia results suggest the region will account for roughly 19% of global emissions by 2050. Given this, it is very likely that the study region will be encouraged by the international community to reduce GHG emissions in the future. The proposition of the Lieberman-Warner Bill in the United States is an example of future geopolitical strategies nations may adopt. Under the Lieberman-Warner Bill section 6003(2), the United States would actively promote international trading partners to take comparable action in terms of baring the costs of climate change policy (L-W Bill, 2007). Interpretation of the bill suggests that the United States would have the option of applying trade tariffs on GHG intensive imports from regions without effective climate policies. The rationale for this approach seems clear. Countries producing goods without internalizing the costs of GHG emissions have an absolute advantage over countries that do. For example, a price on carbon the United States would give cement manufacturers in Canada and Mexico an advantage over those in the United States.

Second, without policy intervention there is little improvement in the GHG intensity per unit energy use in the energy system of the study region. Contributing to this is fuel switching to more GHG intensive fuels in most sectors, due to the large domestic supply of coal. Over the modelling period, the relative share of coal and oil increase from 67% to 73%, while natural gas decreases from 21% to 13%. Over the same period, the low GHG fuels maintain a constant relative share. In industry and electricity generation, a reliance on brown coal continues due to large domestic reserves. In the residential sector, there is a shift from biomass to fossil fuel based energy due to urbanization. Forecasts suggest that close to one billion people will join the urban population by 2050, in addition to strong economic growth. This study indicates that per capita GHG emissions will increase from 1.3 $tCO_2e/cap$ to 2.6 $tCO_2e/cap$ by 2050. With population increase, annual GHG emissions would increase from the 2005 level of 2.6 Gt $CO_2e$, to roughly 7.8 Gt $CO_2e$ by 2050. Recall that to avoid a temperature increase of 2 degree Celsius above 1750 levels, Weaver et al.(2008) found that global GHG emissions would need to decrease from present to 13.6 Gt $CO_2e$ per year in 2050. To put this in context, global GHG emissions totalled 26.6 Gt in 2005.

Third, the electricity generation sector represents the single largest source of GHG emissions in the region. Over the modelling period, the relative share of GHG emissions from this sector averages 40%. The primary challenge for emissions reduction is the reliance on sub-critical thermal coal generation in the region. India for example does not currently have any super-critical coal technology. Emissions from the electricity sector in the study region are estimated at 728 $gCO_2/kWh$ compared to the 566 $gCO_2/kWh$ non-OECD average (IEA, 2007b). In part, this is due to India's coal fired power plants being among the most inefficient in the world, ranging between 27% and 30% conversion efficiency compared to the 37% OECD average (IEA, 2007b).

Fourth, a strong growth in transportation demand is expected to 2050 resulting from an increase in per capita wealth coupled with a decrease in the cost of personal automobiles. In the fall of 2008, Tata Motors of India is to release the "Peoples Car" costing roughly US $2500 dollars (NYT, 2008). The price of the car is half as much as

the cheapest car available today in the study region. Empirical evidence shows that vehicle ownership takes off when per-capita GDP reaches a level of between $3 000 and $10 000, as a large portion of the population can then afford to own a vehicle (Chamon et al., 2008; ADB, 2006).[16] Economic forecasts suggest average per capita GDP (PPP) will reach $10 000/cap by 2050.

## 5.2 GHG Emission Abatement Cost Comparisons

Generating MAC curves with CIMS-Asia served two primary purposes. First, MAC curves provides an estimate of GHG emissions reductions that occur from a range of emissions charges. Second, MAC curves provide an opportunity for comparison of abatement potential across regions, sectors, and with other studies. This study compares the abatement costs generated by CIMS-Asia, CIMS-China, CIMS-Canada and CIMS-AMELA (Africa, Middle East, and Latin America). Figure 20 provides the marginal abatement costs for each of the four CIMS regions.



**Figure 20:   Comparison of MAC curves created by different regional CIMS models**

Source: China and Canada (Bataille et al., 2008), AMELA (Melton, 2008)

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[16] Gross domestic product (GDP) is referred to in terms of purchasing power parity (PPP) - taking into account the relative cost of living and the inflation rates of different countries.

The difference in regional MAC curves is largely a result of the relative size of each region's energy system, and the resulting emissions in the BAU forecast. As expected, there are significantly more emissions available for abatement in non-OECD Asia, AMELA and China than there are in Canada. These variations provide justification for tradable emissions permit schemes. If the goal is to cap emissions at a certain level by 2050, the equimarginal principal states that society will receive the maximum benefit if the regions trade emissions permits until the last unit of emissions abated is of equal cost to all regions (Ward, 2006).

In figure 21 below, removing the influence of the BAU emissions in each region is done by considering emissions reductions as a percentage of the BAU in 2050. When viewed in relative terms, results suggest there is only a slight difference in the emissions available for abatement from these regions of the world, up to a charge of roughly $75/tonne $CO_2$e. A significant finding is that with emissions charges above $75/tonne $CO_2$e, more emissions reductions relative to the BAU are available from Canada then the other developing regions.
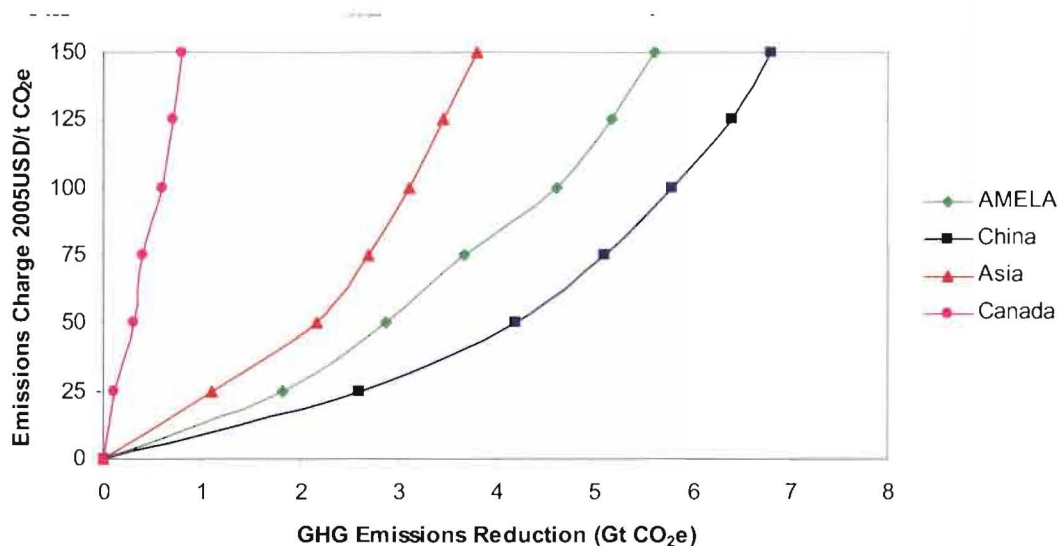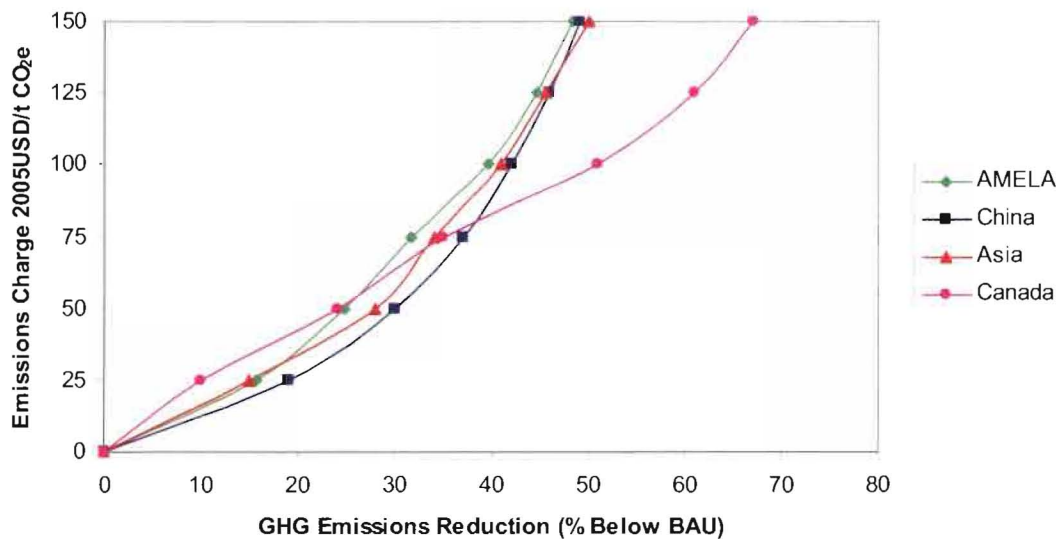


**Figure 21:  Comparison of MAC curves created by different regional CIMS models.**

Source: China and Canada (Bataille et al., 2008), AMELA (Melton, 2008)

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The results displayed in figure 21 are counter to findings of several other studies comparing the relative marginal abatement costs of developed and developing regions (for example see: Ellerman et al., 1998; Sands, 2004). In each of these studies, developing regions have lower relative abatement costs than do developed regions on average. For example, Ellerman et al. (1998) found that with emissions charges up to $100 tonne $CO_2e$ both China and India have much lower MAC curves than do the United States and other developed regions. The following discussion will attempt to explain the difference in the findings of this study.

Bataille et al (2008) came to the same conclusion as this study when comparing the relative MACs of China and Canada using CIMS models. They found that developing regions such as China have rapidly growing economies with a large portion of the population still lacking basic energy services. As large populations currently lacking basic energy services, acquire wealth and access to these services, GHG emissions are added to the reference scenario that are very difficult to abate unless zero emissions services are available (Bataille et al., 2008). Conversely, the populations of developed nations have access to multiple energy service options, and therefore have more options for emissions reduction while maintaining the same level of energy service.

Figure 22 (below) supports the argument presented by Bataille et al. by illustrating the per capita emissions for the four CIMS regions and the world average (IEA, 2007a). Developed regions, such as Canada clearly have more options for reducing emissions without compromising basic energy services on a per capita basis. The average per capita energy related emissions are twelve times higher in Canada than the study region.
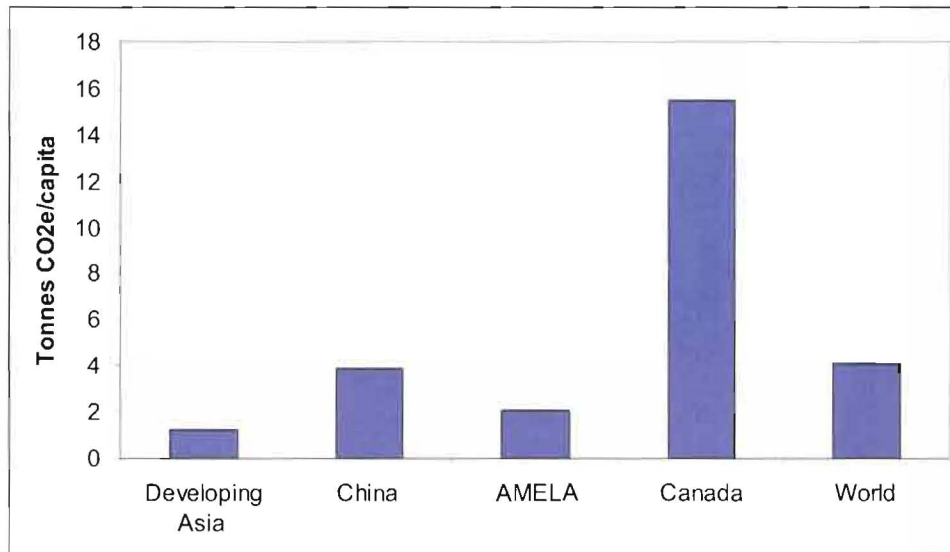
**Figure 22: Energy system related per capita CO2e emissions in 2005**
Source: IEA (2007a)

The rationale provided for Canada having lower relative abatement costs than some developing regions of the world above \$75/tonne $CO_2e$ appears to be sound conceptually. However, the challenge is in providing a rationale in the context of the CIMS frameworks that generated the results. For this, it is necessary to determine the influence of growth in basic energy services on GHG abatement costs generated by CIMS-Asia. Recall that CIMS-Asia relies on the same underlying modelling framework and technology database as CIMS-Canada. Because of this, it is not possible for CIMS-Asia to capture the additional abatement costs associated with a large population gaining access to basic energy services. Another explanation for the unexpected lower relative abatement costs in Canada versus the study region is growth. However, the sensitivity analysis done on the macroeconomic forecast using CIMS-Asia does not support this explanation. Recall that the macroeconomic forecast was adjusted to match the highest and lowest growth rates presented by the IEA, therefore capturing the growth rates of Canada and the study region in the range. The results were that relative abatement costs

generated by CIMS-Asia are not significantly sensitive to growth. For these reasons, the explanation presented by Bataille et al. does not hold for the results of this study.

The differing results could also be a function of CIMS may not accurately represent the energy system of developing countries. One limitation may be that the model framework and base technologies are more representative of developed regions. Although research into the energy system of the study region did conclude that many technologies are comparable, technology data were not complete for the study region. The other CIMS models compared above also use the same technology database, which may indicate why the relative reductions are all so similar.

A final explanation is that for this study the macro-economic loop was disabled to isolate direct emissions reductions for each sector, the same approach was adopted by Tu (2004) in the application of CIMS-China. Having the macro-economic loop disabled would likely decrease the economy-wide abatement potential at higher emissions charges.

## 5.3 An "Alternative" Policy Scenario

The International Energy Agency (IEA) includes an "Alternative Policy Scenario" in each World Energy Outlook. To create this scenario, the World Energy Model is used to estimate the emissions reductions from all of policies that governments are currently considering, and that are assumed to eventually be implemented (IEA, 2007a). For example, the IEA analyzed 80 policies and actions for India that aimed at improving end-use energy efficiencies and improvements to the power generation sector. The rationale for this scenario is to give governments an indication of what reductions are achievable by policies currently considered by each country (IEA, 2007a). For example, the IEA estimates that, if governments within the study region carried out all of the current policies in consideration, emissions reductions of 10% and 25% relative to BAU are available in 2015 and 2030 respectively. The World Energy Model, a top-down CGE model with limited technological detail generated these results (IEA, 2008b).

There are several problems with the "Alternative Policy Scenario" created by the IEA. First, the IEA considers "alternative" policies to be those that a country is expected

to implement, including policies for improved energy efficiency. The issue here is where to draw the line between policy emissions and natural efficiency improvements not driven by increased energy costs that would therefore be part of the business as usual forecast already. Second, from a modelling perspective there are methodological concerns of simulating 80 policies that focus on energy efficiency for one country as done for India. The most obvious concerns involve the risk of not including the rebound effect and the overlap of policies that lead to double accounting. Third, such scenarios are not necessarily a realistic depiction of the policy future, given that they are simply an amalgamation of every policy considered by a region at the time. Fourth, the scenarios do not involve a measurable target to gauge the effectiveness of policies over time. For example, the IEA does not provide any information on the success or failure of policies since 2001 at reducing emissions.

To overcome the downfalls of the IEA's "Alternative Policy Scenario", the recommendation is for a simulation-based approach with targets. As an example, a 24% decrease in business as usual emissions by 2030 could be the target. An energy-economy model can then simulate policies that reach that target. Using CIMS-Asia, achieving the 24% target requires an emissions charge of $4/tonne in 2015 and increasing linearly to $10/tonne by 2030. Compared to managing 80+ policies, this emissions price path provides a very realistic method of reducing GHG emissions.

## 5.4 GHG Emissions Price Paths

Recently, the application of the Earth System Climate Model (ESCM) generated $CO_2e$ emission reduction scenarios for 2050, 2100 and 2500 (Weaver et al., 2008). The purpose of these scenarios was to determine what level of emissions reductions from the reference case are necessary to keep global temperature increase below the commonly agreed upon threshold of a 2.0 degrees Celsius increase from pre-industrial levels (IPCC, 2007a). ESCM model results suggest that with global $CO_2e$ emissions reductions of 50% relative to 2005, temperature increase does not exceed the 2.0 degrees Celsius by 2050.

As a starting point, this study used the 50% reduction from 2005 levels by 2050 (13.6Gt $CO_2e$/year) as a target for climate policy analysis. As previously discussed, equity is an issue in terms of considering an individual nation's responsibility for meeting the above global emissions target. For example, the current per capita emissions of the study region is roughly 1.25 tonnes $CO_2e$/cap compared to the world average of 4.22 tonnes $CO_2e$/cap. To reach the 13.6Gt $CO_2e$/year target by 2050, global average per capita emissions needs to reach 1.89 tonnes CO2e/cap.[17] To explore how the study could contribute to reaching this target, three climate policies were simulated in CIMS-Asia

Results suggest that the study region can reach an emissions target of 1.89 tonnes CO2e/cap with a low emissions charge. An emissions charge of $3/t$CO_2e$ applied in 2011 and increasing linearly to $27/t$CO_2e$ achieves this target. The estimated reduction in GDP from this policy was 0.8%, making this a realistic option for a developing region.

The purpose of simulating the *Bataille* and *Stabilize* policies was to demonstrate how the energy system would respond to relatively high emissions charges. Results indicate that the *Bataille* and *Stabilize* policies result in 48% and 64% reduction in 2050 relative to the BAU. The additional 16% of emissions reduced in the *Stabilize* policy requires increasing the emissions charge from $100 to $250/t$CO_2e$.

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[17] The per capita target assumes a global population of nine billion people be 2050 (UNDP, 2008)

# CHAPTER 6: CONCLUSIONS

This research involved developing and applying an energy economy model for analysis of climate policy in non-OECD Asia. Section 6.1 summarizes the research findings of this study and addresses the research question of this study. Section 6.2 provides policy recommendations aimed at decision makers within the study region. Section 6.3 reviews some of the limitations that faced this project. Section 6.4 summarizes some of the key challenges associated with modelling a developing region of the world. Finally, section 6.5 wraps up with recommendations to guide future research efforts with CIMS-Asia.

## 6.1 Summary of Research Findings

This research project has resulted in two distinct research efforts in the field of energy economy modelling. First, it involved the development of CIMS-Asia, the first hybrid energy-economy model for the non-OECD Asia region using the CIMS framework – incorporating the key elements of technological explicitness, behavioural realism, and macroeconomic feedbacks. CIMS-Asia is capable of generating a technologically detailed baseline forecast of how the study region's energy system will likely evolve to 2050 and how various energy policies can alter the course of the baseline forecast. These efforts have satisfied the first research objective of this study.

Second, the development of a new hybrid energy-economy model has allowed for the generation of new results as BAU and GHG emissions abatement forecasts from 2005 to 2050. Although CIMS-Asia is capable of simulating a wide variety of energy policies, this research focused on policies that place a charge on GHG emissions. The presentation of results from emissions policy price paths has satisfied the second objective of this study. This research contributes to overarching research efforts aimed at

creating a linkage of regional CIMS models in a global framework, meeting the third objective of this study.

**Research Question 1: Can the BAU results assist in guiding climate policy in the study region?**

The most significant finding in the reference scenario is the forecasted annual growth in GHG emissions, increasing by over 300% to reach 7.7 Gt $CO_2e$ by 2050. Compared to forecasts to 2050 for global GHG emissions and population increase, the study region will account for 17% of global emissions and 33% of the global population. These forecasts suggest that the per capita emissions of the study region will be half that of the global average by 2050.

The reference case projections generated by CIMS-Asia to 2050 indicate that significant opportunities exist for GHG emissions reductions. Results indicate that fossil fuels maintain close to a 95% share of the primary energy fuel mix over the entire modelling period. The GHG intensity increases within this mix, as natural gas shares decrease by 10%, oil shares increase by 10%, and coal remains constant. Given these trends in fuel mix, there appear to be opportunities for fuel switching to less GHG intensive fuels. Opportunities exist for reducing the GHG intensity of the energy system, as the current technology mix in the study is inefficient and results suggest little improvements are made in energy efficiency. Within the electricity generation sector, substantial opportunities exist to reduce GHG emissions though improving plant efficiencies, coal washing, and reducing transmission and distribution losses.

**Research Question 2: Are there significant opportunities for GHG emissions abatement at relatively low emissions charges?**

Results suggest that although some low cost opportunities exist for emissions abatement, they are not as low cost as expected. Within the study region, most of the low cost opportunities for GHG emissions abatement are primarily in the electricity

generation sector. This is due to very poor efficiencies in power generating facilities, and very high losses in transmission and distribution.

A comparison of marginal abatement costs from regional CIMS models indicates that there are not low cost opportunities for abatement within the study region relative to other regions. These results are counter to the expectation that developing regions normally have much lower relative marginal abatement costs. In fact, results from the four CIMS models indicates that above US \$75/tonne $CO_2e$ there are more relative emissions available for abatement in Canada versus China, AMELA, and the study region. A sensitivity analysis on the macroeconomic forecasts indicates that the rationale of different growth affecting the abatement costs does not hold for the results of CIMS-Asia. Given that these findings are counter to those of other studies, the following rationale was offered:

1. The base technologies in CIMS do not accurately reflect the low end of the technology efficiency spectrum in developing regions.
2. The base behavioural parameters in the CIMS models do not accurately reflect developing regions.
3. CIMS does not capture GHG emissions from land-use changes, agriculture, and waste.

**Research Question 3: Can the study region contribute to a global GHG emissions reduction target of 5% below 2005 levels by 2050 without negatively effecting economic growth?**

In terms of absolute emissions reductions, the region cannot reduce its emissions to 50% below 2005 levels by 2050 without negatively effecting economic growth. Even with an emissions charge starting in 2011 and increasing linearly to \$250 $tCO_2e$ in 2050, emissions only stabilize at 2010 levels. The above emissions target required an emissions charge starting in 2011 increasing linearly to \$400 $tCO_2e$ by 2050. However, on a per capita basis the study region can contribute to the above target at a relatively low

emissions charge. An emissions price path of $3 tCO$_2$e applied in 2011 increasing linearly to $27 tCO$_2$e by 2050, results in the study region reaching the *Contraction and Convergence* target of 1.9 tonnes per capita by 2050. The study region is one of the few regions of the world that is currently below the per capita emissions target that would result in global emissions reduction of 50% below 2005 levels by 2050.

## 6.2 Policy Recommendations

The previous section provided a summary of the key research findings presented in this study. This section provides policy recommendations aimed at policy makers in the study region in light of the findings of this study.

1. Results suggest that immediate efforts should focus on the electricity generation sector – specifically in moving from sub-critical to super-critical coal technologies. In addition, immediate efforts should focus on reducing the transmission and distribution losses that are more than double the OECD average.

2. CIMS-Asia forecasts that a significant portion of emissions abatement from a charge on GHG emissions results from carbon capture and storage (CCS). This indicates that, in a future with carbon constraints, CCS may provide low cost options for reductions relative to the alternatives. The recommendation is to continue with research and development efforts in CCS technologies.

3. The reference case forecast suggests that GHG emissions from the transportation sector will grow significantly in the coming decades. At the same time, a very large rural-urban shift is occurring with one billion people forecasted to join urban centres of the study region by 2050. For both of these reasons, the recommendation is to plan for low emissions transportation options including walking, cycling, and public transit.

4. Results from CIMS-Asia, and other studies applying regional CIMS models, indicate that the study region would benefit from international policies with flexible market mechanisms. However, results indicate that the opportunity

diminishes with an increase in carbon charge. The recommendation is to support international policy architectures that allow for tradable GHG emissions permits.

## 6.3 Study Limitations

In terms of model development, this research project faced several limitations. Each is explored from the perspective of the three evaluation criteria used to assess the usefulness of a model for analysis of climate policy.

### Technological Explicitness

Data availability was very limited for the study region. Many of the countries within the study region do not actively provide detailed energy sector information, and very few provide any information on technology mix. Some groups, such as the International Energy Agency, do provide aggregate data for developing regions for major sectors but rarely at the sub-sector level. Specifically, data were very limited in the residential, commercial, and some industry sub-sectors.

Almost all of the technologies in CIMS-Asia are the base technologies that exist in CIMS Canada. It is likely that the Canadian technologies do not accurately represent technologies at the lower end of the efficiency scale in developing Asia. If this is the case, CIMS-Asia is likely underestimating the GHG emissions reduction potential that exists in the short run. However, in the long run it would be expected that the current technologies in CIMS Canada would more accurately represent the technologies of Developing Asia due to natural improvements in energy efficiency.

### Behavioural Realism

As previously discussed, CIMS includes three behavioural parameters within the market share equations that influence which technologies are selected within the model. A literature review was unsuccessful in finding any information needed to set these parameters for the study region. For this reason, Canadian behavioural parameters served as a proxy.

**Macroeconomic Feedbacks**

CIMS-Asia is a partial equilibrium model that balances the prices and quantities of the commodities modelled, including fuels, materials and energy services at the sector level. A limitation is that all other economic activity is held constant. In a rapidly growing and changing economy, this may be more of a limitation for modelling developing regions than it is in Canada.

## 6.4 Challenges of Modelling a Developing Economy

Cleary, there are significant differences between the energy system and economy of Canada in comparison the study region. Therefore, there are obvious challenges in attempting to apply a modelling framework from a developed region such as Canada to a developing region of the world. The following will highlight the significant challenges discovered during this study.

**Electrification Rates**

The average electrification rate for the study region is 55%, with a range of 7% to 100%. Applying the CIMS framework requires the assumption that the electrification rate is 100% as in Canada. This poses a serious challenge for policy analysis given that over 900 million people that do not have access to electricity, are assumed to have access in the CIMS-Asia.

**Urban-Rural Wealth Disparity**

There are very significant differences between rural and urban populations in developing regions in contrast to developed regions. Rural populations are very poor on average, surviving by basic subsistence living. In contrast, urban populations are wealthier and demand far more energy intensive goods and services. For example, the IEA estimates that most of the economic growth that is occurring in developing regions is in urban areas (IEA, 2007a). Averaging the rural-urban population of the study region in the CIMS framework is therefore a significant challenge.

**Energy Subsidies**

Within the study region, the selling of energy at below the cost of production is common. For example, electricity rates in India are among the lowest in the world due to government subsidies. As a result, revenue is not available to upgrade generation and distribution system. The electricity generation sector of the study region is one of the most inefficient in the world, with very high transmission and distribution loss rates.

**Non-Reporting and/or Misreporting**

As mentioned, data were a serious limitation of this study. One of the challenges is that many countries within the study region do not actively report energy system data. For example, Tu (2005) found that China misreported coal data. The greatest challenge for this study was in finding consistent data on the technology mix in the study region.

## 6.5 Future Research Recommendations

Given the resource limitations of this study, there are immediate actions that could improve the usefulness of CIMS-Asia. The following list of recommendations for future research would be the next steps if this study were ongoing.

1.  Continuously improve and update the exogenous stock forecast, including energy prices. A sensitivity analysis has demonstrated that the results of CIMS-Asia are extremely sensitive to the exogenous stock forecast. In some sectors, it was necessary to estimate these forecasts using relatively poor data. Further, the agencies that provided the data used in CIMS-Asia update their forecasts yearly.

2.  Improve the accuracy of the technology database in CIMS-Asia. As mentioned, technology specific data and time were both limiting factors. In almost all cases, the technologies of CIMS Canada served as a proxy for technologies for CIMS-Asia. Future efforts could focus on improving the accuracy of the technology mix in CIMS- Asia. Specifically, efforts should focus on the low end of the technology spectrum in terms of efficiency.

3. Investigate the MAC curves generated by CIMS models for developing regions. In particular, explore the reason for the abatement costs of Canada being lower than in developing regions with emissions charges above $75 tCO$_2$e.

4. Provide justification for the current behavioural parameters in CIMS- Asia. First, efforts should focus on the discount rates that are applied by consumers, firms, and governments in developing regions. Given that resources are scarcer, the assumption is that discount rates would be higher in developing countries. Second, focus on the other behavioural parameters to ensure that the current parameters are within an acceptable range.

5. Explore the possibility of disaggregating India and the Rest of Asia into two separate models. Although the region is relatively consistent in terms of growth rates within the energy system, several issues may warrant desegregation. First, it may be strategic form a policy analysis perspective to have India isolated due to the global significance of the energy system. Second, there is a political divide between India and the Rest of Asia in terms of current trade and economic development agreements. Third, the energy system of India is under more state control than the Rest of Asia providing unique challenges for modelling domestic policies. Finally, the primary energy fuel mix is significantly different in India.

6. Continue with efforts of establishing some form of data sharing agreement with other energy economy modelling groups. The data requirements of the regional CIMS models are extensive, in terms of both the current deficiencies and future updating requirements.

# APPENDICES

## Appendix A – Country List

The following 31 countries are included in the model region of CIMS- Asia. These countries represent the non-OECD Asia region, excluding China, as defined by the International Energy Agency (IEA, 2006a).

Afghanistan
Bangladesh
Bhutan
Brunei
Cambodia
Chinese Taipei
Fiji
French Polynesia
India
Indonesia
Kiribati
Democratic People's Republic of Korea
Laos
Macau
Malaysia
Maldives
Mongolia
Myanmar
Nepal
New Caledonia
Pakistan
Papua New Guinea
Philippines
Samoa
Singapore
Solomon Islands
Sri Lanka
Thailand
Tonga
Vietnam
Vanuatu

# Appendix B – Exogenous Macroeconomic Forecast

|  | Units | 2005 | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|
| **Energy Demand Sectors** | | | | | | | |
| Residential | Households (millions) | 158 | 168 | 195 | 213 | 235 | 260 |
| Commercial | m² floor space (millions) | 809 | 984 | 1440 | 1970 | 2580 | 3220 |
| Transportation | Passenger/tonnes kilometres travelled (billions) | 3400 | 4350 | 5960 | 8680 | 13100 | 18800 |
| Chemical Products | Tonnes (millions) | 143 | 178 | 219 | 269 | 291 | 316 |
| Industrial Minerals | Tonnes (millions) | 423 | 515 | 627 | 765 | 828 | 897 |
| Iron and Steel | Tonnes (millions) | 91 | 133 | 238 | 320 | 347 | 375 |
| Metal Smelting | Tonnes (millions) | 0 | 1 | 1 | 1 | 1 | 1 |
| Mineral Mining | Tonnes (millions) | 84 | 94 | 115 | 133 | 144 | 156 |
| Paper Manufacturing | Tonnes (millions) | 9 | 11 | 16 | 20 | 22 | 23 |
| **Energy Supply Sectors** | | | | | | | |
| Electricity Generation | Petajoules | 5990 | 7730 | 10700 | 13300 | 16200 | 19700 |
| Petroleum Refining | M³ (millions) | 554 | 674 | 950 | 1280 | 1330 | 1380 |
| Petroleum Crude Extraction | Barrels per day (millions) | 226 | 221 | 215 | 203 | 178 | 156 |
| Natural Gas Extraction | M³ (millions) | 232 | 265 | 435 | 700 | 853 | 1040 |
| Coal Mining | Tonnes (millions) | 663 | 764 | 1020 | 1350 | 1940 | 3050 |

**Appendix C – CIMS-Asia Reference Run Outputs**

| Energy Consumption (EJ) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
| **Total Primary Energy Consumption** | | | | | | | | | | |
| Oil | 11.4 | 14.9 | 18.0 | 21.8 | 26.2 | 29.7 | 33.2 | 37.0 | 41.0 | 45.4 |
| Natural Gas | 7.9 | 8.9 | 10.7 | 11.8 | 12.6 | 13.4 | 14.4 | 14.9 | 14.9 | 15.0 |
| Coal | 12.7 | 16.1 | 18.5 | 21.0 | 24.0 | 26.5 | 29.0 | 32.0 | 35.8 | 40.1 |
| Nuclear | 0.9 | 1.1 | 1.4 | 1.7 | 1.9 | 2.0 | 2.2 | 2.4 | 2.6 | 2.7 |
| Renewable | 2.4 | 3.0 | 3.6 | 4.1 | 4.5 | 4.9 | 5.4 | 6.0 | 6.6 | 7.2 |
| Other | 0.0 | 0.2 | 0.4 | 0.7 | 0.8 | 0.9 | 1.0 | 1.2 | 1.5 | 1.8 |
| Total | 35.3 | 44.3 | 52.5 | 61.0 | 69.9 | 77.5 | 85.3 | 93.5 | 102.5 | 112.3 |
| **Electricity Generation Energy Consumption** | | | | | | | | | | |
| Oil | 0.2 | 0.6 | 0.9 | 1.2 | 1.8 | 2.3 | 2.6 | 3.0 | 3.3 | 3.8 |
| Natural Gas | 2.8 | 3.8 | 4.8 | 5.8 | 6.3 | 6.5 | 7.0 | 7.4 | 7.6 | 7.7 |
| Coal | 10.3 | 13.0 | 14.9 | 17.0 | 19.4 | 21.5 | 23.9 | 26.7 | 30.2 | 34.2 |
| Nuclear | 0.9 | 1.1 | 1.4 | 1.7 | 1.9 | 2.0 | 2.2 | 2.4 | 2.6 | 2.7 |
| Renewable | 2.2 | 2.7 | 3.2 | 3.7 | 4.0 | 4.4 | 4.8 | 5.4 | 6.0 | 6.5 |
| Other | 0.1 | 0.2 | 0.3 | 0.4 | 0.4 | 0.5 | 0.6 | 0.7 | 0.9 | 1.0 |
| Total | 16.4 | 21.2 | 25.1 | 29.4 | 33.3 | 36.7 | 40.6 | 44.8 | 49.7 | 54.9 |
| **Total Final Energy Consumption** | | | | | | | | | | |
| Residential | 4.0 | 4.9 | 6.3 | 6.9 | 7.5 | 8.1 | 8.9 | 9.7 | 10.6 | 11.5 |
| Commercial | 1.5 | 1.9 | 2.5 | 2.8 | 3.5 | 3.9 | 4.5 | 5.1 | 5.7 | 6.1 |
| Industry | 12.0 | 15.1 | 17.1 | 19.2 | 21.7 | 24.1 | 25.1 | 26.2 | 27.3 | 28.3 |
| Transport | 6.7 | 8.2 | 9.0 | 10.7 | 12.4 | 14.0 | 16.2 | 18.8 | 21.7 | 25.4 |
| Total | 24.3 | 30.1 | 35.0 | 39.6 | 45.1 | 50.1 | 54.7 | 59.8 | 65.2 | 71.2 |

## Energy Consumption (EJ)

| | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Commercial Energy Consumption** | | | | | | | | | | |
| Oil | 0.3 | 0.6 | 1.0 | 1.3 | 1.7 | 2.0 | 2.3 | 2.7 | 3.0 | 2.9 |
| Natural Gas | 0.3 | 0.4 | 0.4 | 0.5 | 0.5 | 0.6 | 0.6 | 0.6 | 0.6 | 0.8 |
| Electricity | 0.9 | 0.9 | 1.1 | 1.1 | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 | 2.4 |
| Total | 1.5 | 1.9 | 2.5 | 2.8 | 3.5 | 3.9 | 4.5 | 5.1 | 5.7 | 6.1 |
| **Residential Energy Consumption** | | | | | | | | | | |
| Oil | 1.6 | 2.1 | 2.9 | 3.4 | 4.1 | 4.7 | 5.4 | 6.1 | 6.9 | 7.7 |
| Natural Gas | 0.9 | 1.2 | 1.6 | 1.7 | 1.7 | 1.8 | 1.9 | 1.9 | 1.5 | 1.1 |
| Electricity | 1.4 | 1.5 | 1.7 | 1.7 | 1.5 | 1.2 | 1.2 | 1.4 | 1.8 | 2.2 |
| Renewables | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 |
| Total | 4.0 | 4.9 | 6.3 | 6.9 | 7.5 | 8.1 | 8.9 | 9.7 | 10.6 | 11.5 |
| **Industrial Energy Consumption** | | | | | | | | | | |
| Oil | 2.6 | 3.5 | 4.2 | 5.3 | 6.3 | 7.3 | 7.6 | 8.0 | 8.3 | 8.5 |
| Natural Gas | 3.8 | 3.5 | 3.8 | 3.8 | 4.1 | 4.6 | 4.8 | 5.0 | 5.2 | 5.4 |
| Coal | 2.5 | 3.2 | 3.6 | 3.9 | 4.6 | 5.0 | 5.1 | 5.3 | 5.6 | 5.9 |
| Nuclear | 3.1 | 4.8 | 5.2 | 5.7 | 6.2 | 6.8 | 7.2 | 7.5 | 7.9 | 8.3 |
| Renewable | 0.1 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Other | 0.0 | 0.0 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 | 0.2 |
| Total | 12.1 | 15.2 | 17.2 | 19.3 | 21.8 | 24.3 | 25.3 | 26.4 | 27.5 | 28.7 |

## Energy Consumption (EJ)

**Transportation Energy Consumption**

| | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|---|
| Oil | 6.68 | 8.12 | 8.98 | 10.57 | 12.26 | 13.47 | 15.24 | 17.25 | 19.50 | 22.54 |
| Electricity | 0.02 | 0.02 | 0.02 | 0.04 | 0.09 | 0.42 | 0.80 | 1.28 | 1.79 | 2.18 |
| Biofules | 0.01 | 0.02 | 0.03 | 0.04 | 0.07 | 0.10 | 0.14 | 0.22 | 0.40 | 0.61 |
| Natural | 0.04 | 0.03 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Hydrogen | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.03 | 0.04 | 0.05 |
| Total | 6.75 | 8.19 | 9.04 | 10.65 | 12.43 | 13.99 | 16.20 | 18.79 | 21.73 | 25.38 |

## GHG Emissions (Gt CO₂e)

**GHG Emissions by Sector**

| | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|---|
| Residential | 0.16 | 0.22 | 0.29 | 0.33 | 0.39 | 0.44 | 0.50 | 0.55 | 0.59 | 0.63 |
| Commercial | 0.04 | 0.06 | 0.10 | 0.12 | 0.15 | 0.17 | 0.20 | 0.23 | 0.25 | 0.26 |
| Industry | 0.82 | 0.97 | 1.14 | 1.30 | 1.50 | 1.70 | 1.78 | 1.86 | 1.94 | 2.02 |
| Transport | 0.48 | 0.58 | 0.64 | 0.75 | 0.87 | 0.96 | 1.09 | 1.23 | 1.39 | 1.61 |
| Electricity | 0.98 | 1.26 | 1.47 | 1.70 | 1.94 | 2.14 | 2.37 | 2.59 | 2.87 | 3.17 |
| Total | 2.48 | 3.10 | 3.64 | 4.20 | 4.86 | 5.42 | 5.93 | 6.46 | 7.03 | 7.68 |

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