Joint Mitigation under the Kyoto Protocol:

A Canada-USA-India Case Study*

Amit Kanudia[1] and Richard Loulou[2]

GERAD discussion paper G-98-40, 1998. Submitted to Energy Policy.

Abstract

In this paper, we use the multi-region version of a detailed bottom-up model, MARKAL, to explore avenues for reducing the cost of GHG abatement in North America through energy and emission trading. The setting of the study is the recent Kyoto Protocol, of which Canada and the US are signatories. We consider two alternate levels of Joint Mitigation, the first within North America, the second broadened to include a non-Annex I country, India. Results indicate overall savings of up to CDN$53 billion (NPV over a 40 year horizon) with North American cooperation, and of about CDN$385 billion when India is included. Inter-regional exchanges and energy policy implications in each region are discussed in some detail.

Keywords: Global Warming, Kyoto Protocol, Joint Mitigation

1. Introduction

Canada and USA are signatories to the Kyoto Protocol of December 1997 (UNFCCC, 1997), along with more than 100 other countries. If the treaty is ratified, the two countries will have to curb their anthropogenic greenhouse gas emissions (CO_2 equivalent of six gases listed in Annex A of the Protocol) so that their average annual emission over the 5 year period 2008-2012 will not exceed those of 1990 minus a fixed percentage (equal to 7% for the USA and 6% for Canada). In order to satisfy the protocol, policy makers will need to answer many questions, such as: Should all reductions be accomplished within each respective country or partly by Joint Mitigation with other countries? What are the sectors and subsectors of the Canadian and US economies that will be asked to effect reductions, and by what amounts? What is the cost of abatement? What are the Policy instruments (e.g. carbon tax, tradeable permits, regulations) that should be chosen to induce the desired abatement in each sector? These questions are daunting, and there is little time to decide what to do, since the present state of Canadian and US GHG emissions (which exceed 1990 emissions by several percentage points) is no cause for optimism.

* This research was partially supported by the Natural Science and Engineering Research Council of Canada, the Fond FCAR (Quebec), Environment-Canada, and the Shastri Indo-Canadian Institute.

[1] GERAD, 3000 Ch. de la Cote-Ste-Catherine, Montreal, Quebec H3T 2A7, Canada. Tel: (514) 340 6032 Fax: (514) 340 5665

[2] GERAD and McGill University, Montreal, Canada.

In this research we attempt answers at several of these questions, with a focus on the efficient allocation of emission reductions to a group of geographical entities (countries or provinces), so as to reach a common group reduction target. Joint Mitigation (JM) is defined here as a generalization of the Joint Implementation (JI) and the Clean Development Mechanism (CDM) concepts described in the Kyoto Protocol. The Clean Development Mechanism (Article 12 of the Protocol) envisages the cooperation between Annex I nations (which are required to limit the emissions) and non-Annex I nations, such as we have assumed between Canada and India in this research. The CDM is assorted with a number of guidelines and restrictions which we do not explicitly model here. Regarding cooperation between annex I countries, the most prominent example has been the agreement between the 15 European Union countries. Therefore, our experiment borrows from both the CDM and the JI provisions of the Protocol, and generalizes them. One practical difficulty of JM as defined here, also present in the CDM mechanism, is that it is unclear what would constitute a ‘reduction’ of Indian (or any other non-Annex I country) emissions, since there is no generally recognized base against which to measure such a reduction (contrary to Canada or USA, where the base for measuring reductions is the 1990 emission level). This difficulty should not be cause for abandoning the JM approach, insofar as JM can potentially bring considerable cost savings, as will be established in this paper. We will therefore define our own ‘reasonable’ base case scenario for India, in order to operationalize the subsequent reductions that can be effected there, and traded with the other two countries.

The aim of this research is limited to finding the cost-effective joint mitigation strategy to achieve a common mitigation target. In this regard, our work provides valuable insights into the common mitigation strategy, identification of sectors and technologies where cooperation can be most effective, and quantification of long-term benefits. The sharing of benefits and the specific mechanisms of technology transfers - two issues which are of considerable concern within the north-south debate - are addressed incompletely, since they fall outside the immediate research agenda of this paper.

The preceding discussion clearly shows that our work is of a prospective nature, meant to analyze the *potential* merit of JM, rather than to make firm recommendations. The insights gained should be useful in examining future extensions and complements to the Kyoto Protocol.

The analysis is based on five advanced, detailed MARKAL bottom-up models of the energy systems of three Canadian provinces (Ontario, Quebec, and Alberta, accounting for 73% of Canadian GHG emissions), the US, and India. The five models have been developed independently by national research teams, and recently harmonized by the authors. The scope of the study is quite broad, and includes the analysis of the merit of Joint Mitigation under various scenarios. Each scenario examines a particular level of cooperation between the players, materialized by the trading of GHG emission permits and/or energy between them. By comparing scenarios that allow or disallow these two types of cooperation, we are able to compute the net advantage of trading.

It is clear that from a conceptual viewpoint, JM is not different from an emission permit trading system limited to the group of countries in the study. The phrase ‘permit trading’ will therefore often be used in this article, although it is not our intention to examine the detailed implementation aspects of such a system[3].

The value of our research also depends on how well our choice of the three countries represents the entire set of countries, as far as the GHG issue is concerned. Ideally, the study should include *all* the main emitters of GHG around the world. On the other hand, since we wanted to retain the technological and sectoral detail of each national or provincial system, we had to limit the study to a small subset of countries, for the sake of computational feasibility. This research should thus be seen as a first step in the modeling and analysis of a much larger set of countries. However, our choice is not arbitrary, as we observe that Canada and the US represent a significant fraction of Annex I economies and GHG emissions, and that India is a fair representative of non-Annex I countries as well. This claim is supported by the demographic and economic statistics in Table 1, which show that the Annex I and non-Annex I sets of countries are fairly, if not exactly represented by our subsets.
In section 2, the methodology is outlined, and the three models are briefly described, as well as the scenarios. In section 3, we present and analyze the results obtained, and we conclude in section 4.

2. Methodology: the MARKAL Modeling system

2.1 General features

MARKAL models have existed since 1982 (Fishbone and Abilock, 1981) and have been modified and considerably augmented since then (Berger et al., 1992, Loulou and Lavigne, 1996, Kanudia and Loulou, 1998). In this research, we have used the most advanced version of the model, developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP), of which the authors are active members.

MARKAL is a detailed technological bottom-up model[4] that computes a dynamic partial equilibrium[5] on energy technology markets over an 8 period horizon. Each period covers 5 years, so that the horizon consists of 40 years. In our study, the periods are centred at years 1995, 2000, 2005, .., 2030. The model uses a detailed, explicit technological description of a region's Reference Energy/Environment System (RES), i.e. a set of activities that have energy or environmental inputs and/or outputs. The RES includes the sources, transformation, transport, and end-uses of energy forms, as well as a set of disaggregated economic demands in all sectors and sub-sectors of the economy. Each

[3] An excellent discussion of permit trading systems is contained in chapter 11 of the Second Assessment Report of the Working Group III of the Intergovernmental Panel on Climate Change (IPCC, 1996).

[4] However, contrary to traditional bottom-up models, MARKAL assumes that economic demands are elastic to their own prices. This feature takes MARKAL some distance toward closing the gap between bottom-up and top-down models.

[5] A dynamic partial equilibrium ensures that the market's demands are satisfied at each period at certain prices computed endogenously. In MARKAL, the prices are equal to the marginal values of the energy and material forms present in the model. However, these marginal prices are not necessarily those of a pure deregulated market, since the model may well include many market imperfections (such as imposed market share limits, taxes/subsidies) that the user chooses to include.

technology is described by its technical parameters (mix of inputs and outputs, efficiency, physical lifetime, availability date, etc.), and by a set of economic parameters, such as its acquisition cost, annual fixed cost, variable costs, bounds on market shares, etc. In addition, each technology has a so-called 'residual capacity' at the beginning of the horizon (1993 in our case), indicating the initially existing capacity and its future profile of abandonment. Residual capacities constitute an accurate and detailed description of the RES as it exists at the initial period.

The technologies are inter-related by flows of energy carriers, materials, and other commodities. Among these flows, atmospheric emissions play a particular role, as they are often the subject of scenarios. In fact, environmental considerations have led to a significant increase of the technological database, as many technologies are specifically devoted to emission abatement. *In fine*, GHG emission reduction may be achieved via energy and technology replacements, conservation measures, industrial process switching, and endogenous reduction of certain economic demands, as explained in the next paragraph. Note that the removal and long term sequestration of GHG is not modeled in our current databases.

In MARKAL, economic demands (e.g. number of apartments to heat, kilometres of urban car travel, or tonnes of aluminum to produce) are specified exogenously only for the base scenario. When other scenarios are run, the demands may be altered endogenously by the model, since they are elastic to their own prices[6]. As already noted, this confers greater economic scope to the model, and captures a great deal of the interaction between the energy system and the economy (see Loulou and Lavigne, 1996, for a more substantial discussion of this point).

A MARKAL model run is fully determined by four types of data: the technological database, the demand scenario, the prices of imported energy forms, and the environmental scenario. We will discuss constructed scenarios in the next section.

The 'engine' used to compute the partial equilibrium is Linear Programming. The objective function minimized is the sum of direct costs (investment, O&M, variable costs, taxes/subsidies) and of the loss of consumer surplus resulting from any change in the demand levels compared to the base case. The physical, logical, financial, and policy conditions of the RES are represented by constraints in the L.P. (equalities and inequalities). A typical MARKAL model may have from 5,000 to more than 12,000 constraints, depending to the level of detail and the number of periods.

MARKAL has two additional capabilities which give it much flexibility, namely the handling of uncertain events (Kanudia and Loulou, 1998, Loulou and Kanudia, 1997), and the multi-regional feature (Loulou et al., 1996). In this study, we have not modeled

[6] Since the price of a particular demand is also endogenously determined in the model, a special mathematical device is used to implement the price-demand relationship, see Loulou and Lavigne (1996) for details. In this project, we have actually deactivated the elastic demand feature, so as to obtain a purely technological response from the various energy systems to the environmental constraints.

uncertainties. On the other hand, the multi-regional feature plays a central role in our scenarios: it allows several MARKAL models representing different regions to be merged into a single model, with a single joint objective function to minimize, and with special exchange variables representing the trading of various commodities between the regions. When forming the joint objective function, the user may choose to simply add the costs of each region, or may form a weighted sum of these costs, in order to reflect the difference in the welfare functions of the regions being assembled. Our assumptions in this context are given in section 3.

The five regional MARKAL models: a brief description
The detailed descriptions of the databases have appeared in previous publications (for example, see Loulou et al., 1996). Figure 1 is a synthetic view of the Ontario Reference Energy System (RES), indicating the level of disaggregation in each sub-sector, via the number of technologies used to describe it. The other four models are of quite comparable size and detail, with somewhat less end-use detail in the Alberta and India models. All five models are nevertheless much more detailed than the global models used for international mitigation in the extant literature.

It is worth stressing here some technological assumptions built into the five databases. In general, it may be said that the five models have very comparable sets of technologies, whenever these technologies are not geography-specific (such as hydroelectricity, or solar potential, etc.). For instance, natural gas fuel cells, transportation vehicles, or electric baseboard space heaters are modeled identically in all systems. However, there is one important exception to this: nuclear electricity generation, which has been allowed in India and Canada, but not in the USA, for reasons that are socio-political more than technical. In Canada, the implementation of new nuclear plants is authorized only in 2020 and later, whereas in India, it may start as early as 2010.

2.2 Assumptions and Scenarios

The scenarios are built around two sets of assumptions. One set pertains to the future economic outlook and the other to the carbon mitigation level and trading strategies.

Macroeconomic Growth
Throughout this research, we have used a single scenario for base case economic demands and world energy prices. In Canada and the US, the underlying assumption is that GDP grows at a moderate rate until 2020, and then slows down. The rates vary slightly across the three Canadian provinces and the US, but remain within the 2.1 to 2.4% bracket until 2020, and within the 1.7-2.0 bracket after that date. Of course, each demand segment has its own specific growth pattern in the scenario. Residential and heavy industrial demands grow more slowly than road and air transportation, commercial, and light industry demand segments. We have followed government forecasts to establish our demand growth rates. The prices of crude oil and gas converge in 2005, and on average grow at 1% /yr. until 2010, and then stagnate at their 2010 levels.

The story is quite different for India. Following the economic liberalization policies, the Indian economy is undergoing a market-oriented transformation. The past is thus inadequate to forecast long-term future trends and scenarios. We have used logisitic regression for demand projections, where we incorporate expert judgement via a

saturation level for the parameter being estimated. The logistic curve is appropriate for such estimates in the developing countries with rapidly rising initial trend followed by a saturating trend. These projections correspond to a continuation of the current trend observed in annual growth of GDP (around 6-7% per year), saturating to an annual growth rate of 2 percent by the end of the next century.

Emission Constraints
The Kyoto+ target: Consists of the Kyoto Protocol target for 2010 (i.e. 94% of the 1990 emission level in Canada and 93% in the US), extrapolated to 80% of 1990 emissions in 2035, for both countries. Emission levels at intermediate periods between 2010 and 2035 are interpolated linearly.

Cooperation Scenarios
Four contrasted scenarios are studied, each representing a particular combination of conditions on three elements: GHG emission reduction, the possibility of electricity trade between the regions (i.e. between Quebec and the US), and the possibility of cooperation on GHG mitigation between each pair of regions. The scenarios are described in Table 2 below.

Remarks:
1. *Permit Pricing:* The price at which permits are sold is not directly relevant to the determination of the globally optimal strategy, since when several models are jointly optimized, the revenues and payments cancel out. However, a price is quite essential in ensuring a realistic allocation of the benefits of joint mitigation. In the results presented in section 3, permits are priced at their marginal value[7] in the corresponding optimal LP solution. Such a pricing scheme is compatible with conventional perfect market economics, although it could be unrealistic when market imperfections are present (for example, if the market for permits is oligopolistic rather than atomic).
2. *Energy trading:* In all scenarios, it is assumed that *natural gas trading* within Canada and between Canada and the US is allowed, and endogenously determined by the model. The reason for this is that the North American gas market is mature and fully integrated. Such is not the case of *electricity trading*, which requires significant policy decisions for its future development, as well as investments in new transmission lines. Here is how we have modeled the electricity trade in each scenario: in the Base Case and the Kyoto-NC scenario, no electricity trade expansion is allowed between Canada and the US beyond the current line capacities (However, Quebec-Ontario electricity exchanges are fully allowed and endogenous to the model). In the other two scenarios, unlimited investment in new transmission capacity between Quebec and the US, is endogenous to the model. Just like permit trading, electricity and gas are priced at their respective marginal values when computing the net trade revenues of the trading partners. Note that the Base, the Kyoto-NC, and the Kyoto-CU scenarios involve running the four North American models jointly as one multi-regional model with the appropriate trade variables to endogenize natural gas and/or electricity and permit trading. The Kyoto-CUI scenario requires running all five models jointly as a single model.

---

[7] The marginal system value (or shadow price) of a commodity is readily obtained as the optimal dual value of the balance constraint of that commodity in the MARKAL equilibrium solution.

3. *The multi-region Objective function:* Simply adding the three country wise costs (after converting to a common currency via the market exchange rate) amounts to assuming that the three countries have comparable utility functions. We have made this assumption in the scenarios run in this research. In a side study, not reported here, we had put a weight of 4 (rather than 1) on the relative utility of a dollar in India. The conclusions reported in this article have proved to be quite robust to the inclusion of this factor, as the emission trading reduced only by about 20%. The value of 4 is not fully justified, but is close to the current Purchasing Power Parity (PPP) of a dollar in India compared to Canada or the US. While we do not claim that this method is totally exempt of criticism, we believe that it represents a useful sensitivity analysis on the JM principle. The difficulty of choosing a multiplier is further compounded by several factors: the PPP may be widely different in different sectors of the economy, and furthermore, it is not known how the PPP will evolve over the next 40 years. The use of a Multi Regional General Equilibrium model would alleviate some of these difficulties, since the weights assigned to the regions would be endogenously determined (see Manne and Rutherford, 1994). However, such an approach would make the models non-linear and unwieldy, given the size of our databases.
4. *Provisions under the Kyoto Protocol:* Kyoto Protocol allows the cooperation as modeled under the Kyoto-CU scenario. However, the involvement of developing countries is restricted to approaches like the CDM through specific projects. Such arrangements, unless strategically coordinated under a very long-term cooperation plan, may turn out to be marginal and far from the most cost-effective strategy. What we model in the Kyoto-CUI scenario is a long-term and strategic cooperation between North America and India. Once a Base Case scenario for Indian emissions has been defined and agreed upon, any reduction of Indian GHG emissions below that base line may be used by Annex I countries (Canada and the US in our case) to reduce their own commitment under the Kyoto Protocol, in exchange for monetary compensation to India via permit purchase.
5. *Model size and computational time:* The scenarios described above lead to LP models with about 45,000 rows and 60,000 columns. Most of these were solved in less than 10 minutes using the interior point solver of CPLEX-5, on a PC with a 400 MHz processor.

3. Results and Analysis

3.1 Mitigation Costs (All dollars are Canadian 1995 dollars).

An important global indicator of the severity of the Kyoto Protocol is the total discounted cost incurred by a country to meet its obligations under the protocol. These costs are shown in the top section of Table 3, as additional (relative to the base case) total costs incurred by each country under each scenario. These costs include the direct costs incurred within the energy system, minus revenues accrued, plus payments for net permit and energy purchases. Without any international cooperation, the Kyoto+ target (Protocol plus the post-2012 assumptions of this paper) costs 52.7 Billion or the equivalent of about 0.4 % of the discounted GDP for Canada and 654 Billion or 0.4 % of GDP for the US[8].

[8] The percentages of GDP are provided only to give a sense of scale of the costs. The net impact on GDP is not computed by our models.

The lower section of Table 3 indicates the cost savings resulting from cooperative Joint Mitigation scenarios: thus, the Canada-US cooperation results in an overall saving of $53 Billion. A third of this goes to Canada and the rest to USA. This split is based on the assumption that prices of the endogenously traded commodities, namely GHG permits, Electricity and Gas, are equal to their marginal values. North American cooperation reduces the US costs by about 2% and the Canadian by about 25%. The reason for this asymmetry of the benefits accrued to each country lies in the fact that Canada exports significant amounts of electricity under Kyoto+, thus cashing substantial revenues from the USA.

The situation is dramatically altered when India is allowed in the JM agreement (scenario CUI). In this scenario, savings compared to NC amount to $385 Billion globally for the three countries, split as follows: the USA cuts down its cost by $221 Billion (i.e. more than 30% of its cost in the NC scenario), and Canada reduces its cost by $24 Billion (35% of NC costs). India obtains a net benefit of $140 Billion, which represents about 0.6 % of its discounted GDP. The incremental benefit from the three-country joint mitigation for Canada is *smaller* than that for the US. This is due to the large decrease in electricity and gas exports from Canada to USA when India becomes a JM partner, as can be seen from Figure 4 and Figure 5.

The marginal costs of GHG abatement (Table 4) show another facet of the cooperation: in the Canada-US scenario, the marginal cost always lies between the NC marginal costs of Canada and the US. This is because JM “equalizes” the abatement options of the two countries.

Note that the marginal abatement cost is distinctly lower with Indian cooperation, even after a substantial export of emission permits by that country. One of the reasons is the continuous build-up of technology stock due to high economic growth throughout the model horizon. This makes large abatement possible with *different* investments rather than *additional* ones. For example, under Kyoto scenarios without India, the power sector investments in USA are about 70% higher than the base case. Cooperation with India reduces this figure to about 40%. But the cooperation results in almost no *additional* investment in the Indian power sector.

3.2 Emission and Energy Trading

Emission and energy trading cannot be dissociated, since they play similar roles[9] toward the attainment of the Kyoto+ target. Overall, the Kyoto target induces large changes in the energy trade between Canada and the US, and JM introduces large emission trading as well.

Under the North American cooperation scenario (CU), Canada buys GHG permits from USA for the first ten years and sells permits to the US in later years (Figure 2). However, it sells electricity to the US during the whole horizon (Figure 4), and it increases its

[9] Exporting hydroelectricity reduces emissions in the importing country and does not increase them much in the producing country. This explanation extends to natural gas exports only if gas displaces other fossil fuels with more carbon content, e.g. coal or oil.

natural gas exports to the US as well, compared to the Base Case (Figure 5). Overall, Canada is clearly a direct exporter of emission permits, and an indirect one via electricity and/or natural gas sales. Note that both the electricity and gas exports are much larger in the early periods than in the later periods. This is because, in both cases, Canada has limited total endowments of these resources, and that it is cost effective to use these resources locally in the later periods than to export them. Overall, Canada's *cumulative* gas extraction remains remarkably constant across scenarios, averaging about 5200 PJ per year.

With India as a JM partner (CUI), both Canada and USA buy large amounts of GHG permits from India, throughout the model horizon (Figure 3). As will be seen in the discussion of GHG emissions of subsection 3.3, the North American permit purchases from India represent about 30% of the total abatement (computed from base case), leaving 70% of the effort to local abatement within North America.

Note also that Canadian energy exports to the US drop dramatically, relative to their levels when India was not a JM partner (Figure 4 and Figure 5). This does not mean a corresponding drop in primary energy extraction in Canada, but rather a redirection of Canadian resources for national consumption [10]

3.3 Key Energy Sector Results

***Canada*[11]**

Average annual base case emissions in the post-2010 period are 37% higher than the 1990 level. Under the assumptions of this paper, the post 2010 emissions are about 13% below the 1990 level under Kyoto NC and CU scenarios (Figure 6), whereas under cooperation with India, Canada is able to emit 7% higher than the 1990 level. Therefore, Canada effects about 60% of its total abatement locally (as measured by the difference between base case emissions and the Kyoto target), and the rest via permit purchases from India.

Looking at the composition of the primary energy consumption (Figure 7), coal is the most significantly affected source of energy. It grows more than two folds over the horizon in the base case, as it is a cheap electricity option for Ontario and Alberta. Its average contribution in the post-2010 period decreases from about 15% in the base case to less than 1% under Kyoto-NC scenario. To compensate for coal decline, significant increases are seen in the consumption of hydro electricity, nuclear electricity, and biomass. Gas and oil products are much less affected. Cooperation with India results in the substitution of some of the nuclear energy with natural gas.

Coal based electricity generation has an 18% share in 1995, which more than doubles by year 2030 under the base case. The share of coal in power generation drops to around 1% on average during the post-2010 period under the Kyoto-NC scenario (Figure 8).

[10] The detailed analysis of the Kyoto impact on the Canadian energy system, under various inter provincial cooperation levels, is further conducted in a companion paper.

[11] A more detailed analysis of Canadian results under these and other scenarios in being written and will be the object of a sequel paper.

Conversely, the share of non-fossil based electricity (renewables plus nuclear) which has a decreasing trend in the base case, reaches on average close to 90% in the post-2010 period under the Kyoto scenarios without India (the remaining 10% is gas based). Cooperation with India results in significantly higher gas based electricity generation in the post-2010 period. On average, it contributes about 20%, which is nearly double its base case share. North American cooperation results in hydro and nuclear capacities approaching 68 and 31 GW respectively, by year 2020. Under cooperation with India, the cost incentive for electricity exports and local GHG abatement eases, and the nuclear capacity trajectory reverts to the base case, i.e. no fresh investment. This is an important finding for Canada, since the acceptability of nuclear is far from being established in that country.

As the electricity generation sector is already relatively "clean" in Canada, it alone is not enough to reach the reduction target set in this research. Transportation accounts for about 26% of the aggregate final energy consumption, and the technological and land resources required to support substitution of oil with alcohol fuels exist. These two facts together make the transportation sector a strong candidate for reducing GHG emissions. Significant penetration of alcohol fuels begins only in year 2010, and it meets between 13 and 22% of the entire transportation energy needs in the post-Kyoto period (Figure 9), depending on the level of cooperation.

USA

In the base case, the average annual emissions in the post 2010 period (Figure 10) increase by 21% over the 1990 level. Under Kyoto+ without any cooperation, the corresponding emissions are about 13% below the 1990 level. The reductions are mainly effected through the substitution of coal with natural gas, renewable electricity, and biomass at the primary energy level (Figure 11). The emission trajectory under the Kyoto agreement scenario does not change markedly under cooperation with Canada. However, under cooperation with India, the average annual post-2010 emissions are 2% below the 1990 level. Therefore, even under Indian cooperation, the US still effects more than 70% of its emission abatement on its own territory.

The electricity generation sector brings about the bulk of the GHG emission reduction. The contribution of coal based electricity decreases from an average of 50% under the base case to under 4% in the post-2010 period under the Kyoto scenarios without India (Figure 12). Significant premature abandonment of coal based capacity is observed in later years. The gap is filled by electricity from natural gas fuel cells and non-hydro renewable sources (wind and solar). Cooperation with India prolongs the coal based electricity production, and reduces the penetration of fuel cells and other renewable sources. However, as was observed for Canada, the gas based electricity generation is the highest under cooperation with India. It supplies almost half the electricity demand in the post-2010 period. This is not surprising, as natural gas is quite a good way to abate GHG emissions when a moderate-to-low reduction target is imposed on a coal rich system, but less so when more severe abatement is required. Substitution with natural gas reduces the electricity consumption in residential and commercial sectors under all Kyoto+ scenarios.

Under the North American cooperation scenario, there are heavy imports of electricity from Quebec (Figure 4), which quickly climb up to 100 PJ per year and reach over 500 PJ in the year 2020. Under cooperation with India, imports of electricity reduce to zero in later years.

India

In the base case, the fast economic growth results primarily in the use of the only abundant domestic resource, coal (Figure 13). On the average, coal constitutes a little under half the commercial primary energy consumption in the base case. The aggregate primary energy, coal consumption, and annual GHG emissions, all increase about three folds over the next forty years (much less than GDP, which increases about five fold). Domestic natural gas runs out in year 2020. The coal based electricity generation capacity approaches the 150 GW mark in 2030 (which is less than half the existing coal based capacity in USA today). This capacity meets about 60% of the entire electricity requirement. The preponderance of coal in the electricity sector, coupled with the fact that Indian emissions are restricted only to those in the base case scenario, makes India a prominent seller of GHG permits to Annex I countries such as the USA and Canada.

Under cooperative JM with North America, coal stabilizes at a little *under* the 1990 level beyond year 2010 (Figure 14), a dramatic change from base case. The shares of natural gas, nuclear and renewable energy increase. By year 2030, Indian emissions are only 65% of those in the base case (Figure 15). Almost the entire reduction originates in the electricity generation sector. This is a favorable condition for India, as it is far easier for the Indian government to influence the power sector decisions rather than the fast growing, liberalized end-use sectors. The industrial sector also makes a contribution, as natural gas and commercial biomass substitute about 10% of the coal over the entire horizon. The main transformation in the electricity sector is the partial replacement of coal technology with natural gas based fuel cells (Figure 16). Some increases in hydro, nuclear and other renewable sources (wind, solar) complement the fuel cell development. The present technology mix changes somewhat prior to 2010, and in a big way in year 2010, giving India sufficient time to plan for a Joint Mitigation possibility. The increased consumption of natural gas exhausts the domestic reserves five years earlier than the base case, and increases its average annual gas imports by about 60%.

4. Main Policy Implications and Conclusion

For Canada

For Canada, energy trading is more advantageous than emission trading, if the Kyoto+ target becomes a reality. However, should Permit Trading (including with non-Annex I countries) become widespread, Canada would benefit from joining in it. Overall benefits from permit or energy trading are appreciable, as they decrease the cost of abatement by up to 30%. Under a joint mitigation regime, Canadian provinces would have to closely examine the potential shifts of their gas and electricity sales, the shift being away from US exports and towards internal markets. For Quebec hydro electricity, it is crucial to quickly and accurately identify the exporting possibilities, and to make the correct and timely investments in transmission line capacity (either towards Ontario or towards the US[12]). The problem is less acute for the investments in hydro production capacity, since more capacity would be needed whether or not the generalized JM is involved. The same is true of Alberta gas exports, which would remain fairly stable irrespective of the destination of the exports (i.e. Eastern Canada or the US). Ontario is also affected by the existence or non-existence of a JM scheme, but in a different way, since it is a buyer rather than a seller of permits and energy. Ontario would react differently in the presence of a JM scheme than without it, buying more permits in the first case, and more energy in the latter case. Similarly, Ontario's nuclear option is desirable only in the absence of JM.

For USA

Although the abatement costs as a proportion of the GDP are not very high, the absolute numbers are huge. Therefore, USA has to trade a very high volume of permits to have a significant impact on the overall costs. A non-Annex I country like India proves to be an ideal partner for this purpose. We do not know at this time about the emission targets that might eventually be proposed for the non-Annex I countries, but we can safely assume that their JM potential would be high. The energy and emission trading options with Canada have a relatively small impact, but they are certainly appealing to the states close to Quebec, for which they represent a rather large "clean" supply source of electricity.

For India

A Joint Mitigation scheme such as the one analyzed in this research, would have significant benefits for India, derived from the selling of emission permits. Although the current Kyoto Protocol's CDM does not quite allow such wholesale permit trading between Annex I and non-Annex I countries, it is quite possible to identify specific projects within India and to relate them directly to GHG abatement. Examples would be: gas fuel cells for electricity production, solar and wind technologies, and elimination of coal in certain industries, which would be strong candidates for CDM. Furthermore, the profit sharing proposed in this article (based on marginal cost pricing of permits), while perhaps not perfect, appears to be quite satisfactory for India and the USA. In order to effect the GHG abatement under JM, India will require more than 3.5 Tcf gas imports (annually) by year 2010, and more than twice that amount by 2030. Reliable and stable sources of gas imports will therefore have to be secured. The economic feasibility of a 0.5 Tcf/yr. pipeline from Iran has already been established. Other sources like Turkmenistan are being considered. LNG imports from Qatar, Malaysia, Oman, and Thailand are also possible. The electricity prices as well as the prices of other products would increase in India, if JM is implemented. Part of the proceeds from permit sales would have to be recycled to alleviate socio-economic perturbations provoked by these changes.

Conclusion

The climate change negotiations leading to the Kyoto Protocol have progressed towards binding emission limitations commitments by developed nations. The global cost effectiveness of the emissions limitation shall require cooperation with developing countries where significant, cheaper mitigation opportunities can be found due to the rapidly changing technology stock. The analysis of this paper suggests that cooperation between Canada (Ontatio, Quebec, and Alberta), USA, and India can generate a net savings of $ 385 billion over the next forty years.

A vital consideration for the success of the joint mitigation programme is the sharing of benefits. In the absence of carbon market, the sharing has to be based on the mutual

[12] An intriguing question arises concerning the possibility of building power connections that would be usable for exports either to Ontario or to US, with minor modifications. The geography of the region does not preclude such a robust solution, which should be studied further.

negotiations. When the carbon market develops in the long run, the market price of carbon can decide the sharing of the benefits.

The CDM/JI rules under the Kyoto protocol are still ambiguous and more restrictive than the ones assumed in this research. We treat CDM strategically and model the potential options dynamically and in an integrated manner. This is in contrast to the conventional project oriented static CDM analysis that considers projects in the absence of other options. Any cost-effective emission mitigation regime will require a sustained cooperation among nations over the next century. The strategic joint mitigation shall be critical for the success of such a regime. If India, with other non-Annex I nations, has binding mitigation targets (below their base case) in the future, then the potential for cooperation may be reduced. This scenario can also be modeled by the approach followed in this paper.

We do not want to belittle the practical difficulties that such a strategic JM scheme may encounter, the most obvious one being to reliably define the emission base line for every non-Annex I country, against which abatement will be measured. However, we do think that our scheme is a way to discover and evaluate globally cost-effective abatement strategies, a very desirable goal indeed, and one that is explicitly mentioned in the UNFCCC (1992).

The uncertainties on future events, including the targets and timetables, can be modeled by the stochastic MARKAL models for the three countries. This is on our agenda for short-term future work. Besides, an important improvement for future analysis shall be the inclusion of GHG sinks in the MARKAL database in all models.

***

Acknowledgments

We wish to thank P.R.Shukla of the Indian Institute of Management, Ahmedabad, for his useful comments on the interpretation of the CDM and JI provisions of the Kyoto Protocol. The short discussion of the gas supply sources for India which appears in the conclusion of this article is inspired by a presentation made by P.R. Shukla at a Montreal Workshop held on June 15, 1998.

The authors also extend their thanks to Sam Wong of Alberta Research Council and Morgan MacRae of the Canadian Energy Research Institute for providing the initial Alberta Database, and to Phillip Tseng of the US Department of Energy and Gary Goldstein of Decisonware for providing the US database. Although our work depended on their kind help, we must of course retain full responsibility for any assertions and comments made in this article.

REFERENCES

Berger, C., Dubois, R., Haurie, A., Lessard, E., Loulou, R., and Waaub, J.-P. 1992 Canadian MARKAL: an advanced Linear Programming System for Energy and Environment Modeling, INFOR 20, 114-125.

Fishbone, L. G. and Abilock, H. 1981. MARKAL-A Linear Programming Model for Energy Systems Analysis: Technical Description of the BNL Version, International Journal of Energy Research 5, 353-375.

IPCC. 1996. Climate Change 1995: Economic and Social Dimensions of Climate Change, J.P Bruce, H.Lee and E. Haites (eds), Cambridge University Press, Cambridge, U.K.

Kanudia A. and Loulou R. 1998. Robust Energy Technologies via Stochastic MARKAL: The case of Quebec, European Journal of Operational Research, Vol. 106, No. 1, 15-30.

Loulou, R., and Lavigne, D. 1996. MARKAL Model with Elastic Demands: Application to GHG Emission Control, in Operations Research and Environmental Engineering, C. Carraro and A. Haurie eds., Kluwer Academic Publishers, Dordrecht, Boston, London, pp. 201-220.

Loulou R., Kanudia A., and Lavigne D. 1996. GHG Abatement in Central Canada with Inter-provincial Cooperation, Energy Studies Review, Vol. , No. 2, pp. 120-129.

Loulou, R. and Kanudia A. 1997. Minimax Regret Strategies for Greenhouse Gas Abatement: Methodology and Application, GERAD discussion paper G-97-32.

Manne, A.S., Rutherford, T. F. 1994. International trade in oil, gas and carbon emission rights: an intertemporal general equilibrium model, Energy Journal, Vol. 15(1), 57-76.

UNFCCC. 1992. United Nations Framework Convention on Climate Change- Articles, United Nations, New York.

UNFCCC. 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change, United Nations, New York.

Table 1 Basic Statistics of the three Countries studied

	Population (Billion people)	**GHG Emission** (Billion tonnes CO_2)	**GDP** (Trillion $)
Canada + US	.3	5.1	7
% of Annex I	23%	40%	32%
India	0.95	0.77	0.54
% of non-Annex I	23%	13%	12%

Table 2 The Four Cooperation Scenarios

Scenario	**Description**
Base	No GHG emission constraints; gas trading allowed within North America
Kyoto-NC	US and Canadian emissions each constrained individually as per Kyoto+ Target. Gas trading allowed in North America
Kyoto-CU	US and Canadian emissions constrained jointly as per Kyoto+ Target; Gas trading allowed as before, and Quebec-US may exchange Electricity; No permit exchange with India
Kyoto-CUI	Same a Kyoto-CU, but in addition, India may sell emission permits to any of the other two countries

Note: The GHG reduction in the period 2008-2012 mentioned in the Kyoto Protocol, has been modeled as follows: the MARKAL model emissions account only for the energy sector's emissions, which represent 77% of total anthropogenic GHG emissions in Canada and US. Therefore, the Canadian reduction target has been set at 6% *(1/0.77) = 7.8% *of the energy sector's 1990 emissions*, and US reduction target at 7%*(1/0.77)=9.1% of the energy sector emissions in 1990. After 2012, it has been assumed that the reduction effort would not cease, but rather that additional reductions would be imposed reaching 20% of 1990 levels in 2035.

Table 3 Aggregate Discounted Costs Over the Model Horizon (Billion $)

	Canada	**USA**	**India**	**Total**
Incremental Costs over Base				
Kyoto: NC	67	656	0	722
Kyoto: CU	50	620	0	670
Kyoto: CUI	43	435	-140	338
Savings over NC				
Kyoto: CU	17	35	0	53
Kyoto: CUI	24	221	140	385

Table 4 Marginal Costs of GHG Abatement Under Kyoto+ ($/Tonne of CO_2-Eq.)

	2010	**2015**	**2020**	**2025**	**2030**
No Cooperation					
Canada	95	110	94	141	352
USA	48	85	216	388	245
North American Cooperation					
Canada+USA	54	85	190	358	245
North America + India					
Canada+USA+India	38	44	60	85	72

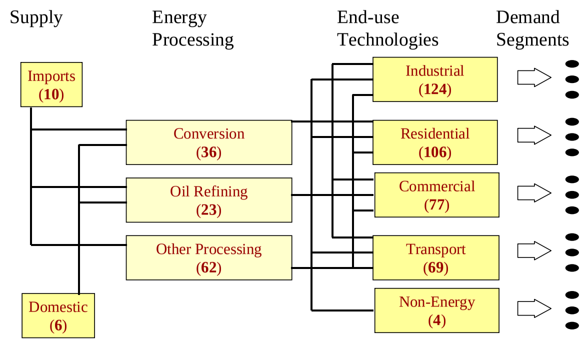

Figure 1 RES of MARKAL Ontario

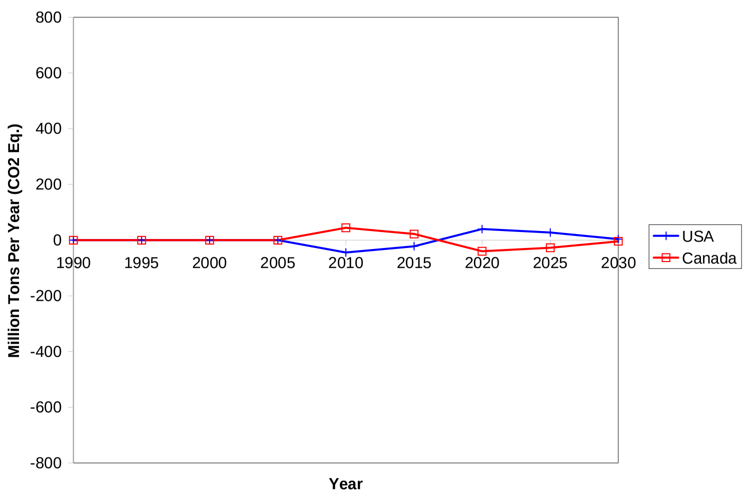

Figure 2 Purchase of GHG Emission Permits under North American Cooperation

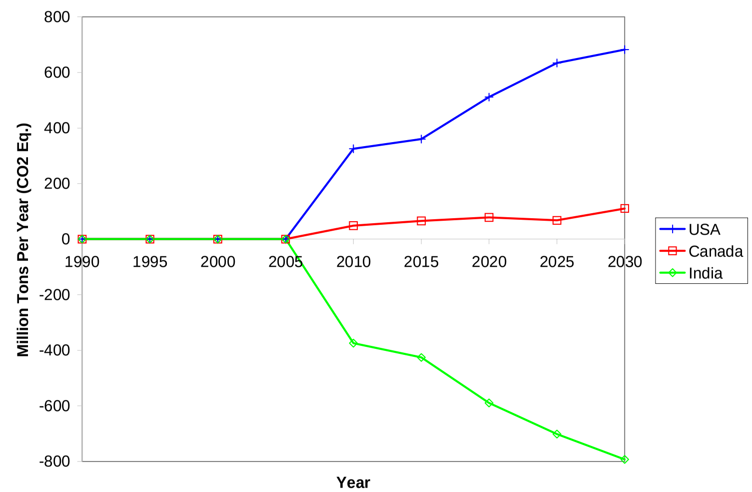

Figure 3 Purchase of GHG Emission Permits under North America+India Cooperation

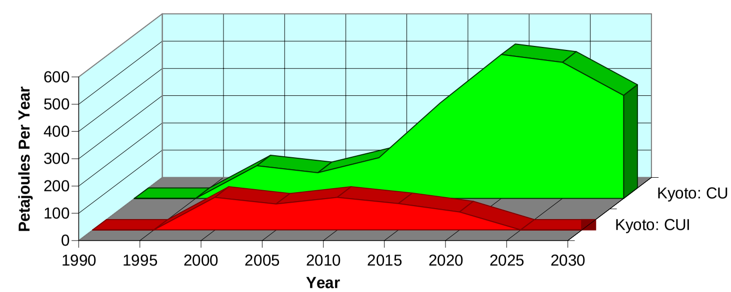

Figure 4 Electricity Import by USA from Quebec

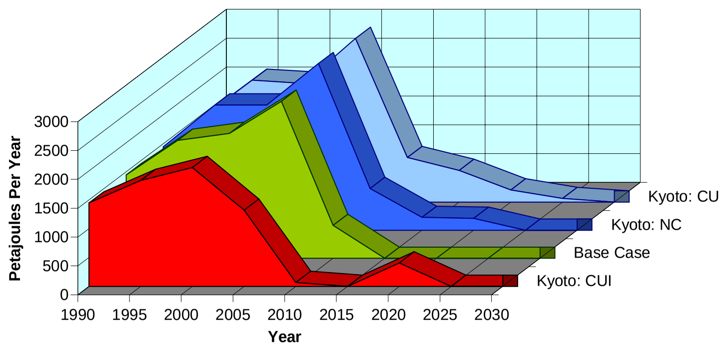

Figure 5 Import of Natural Gas by USA from Alberta

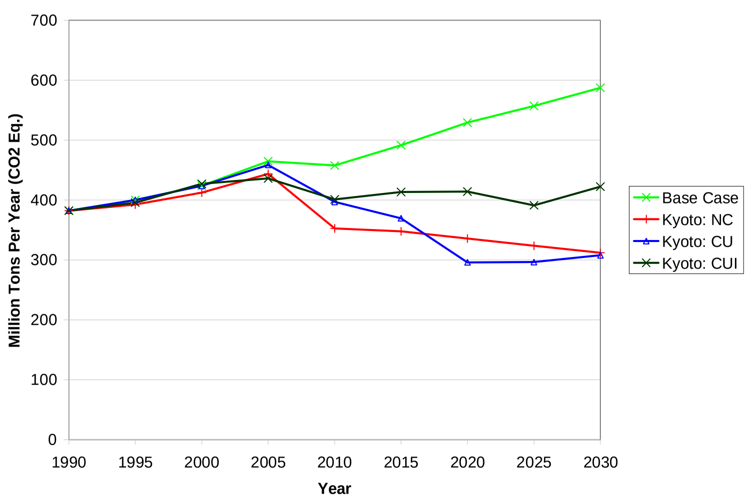

Figure 6 Annual GHG Emission for Canada

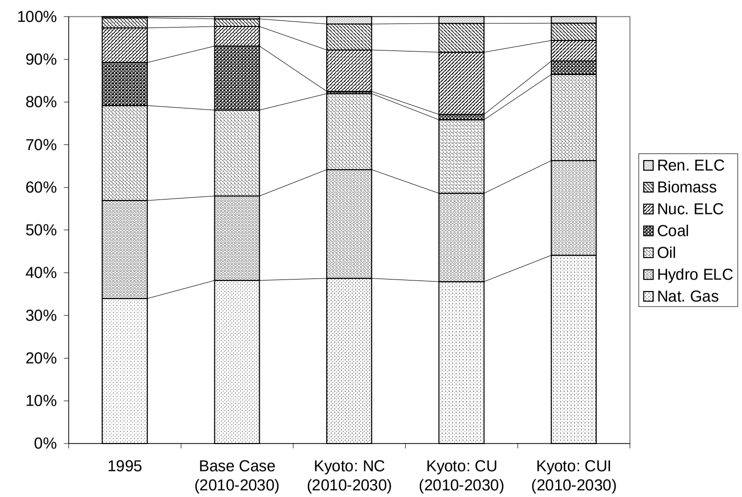

Figure 7 Composition of the Primary Energy Consumption for Canada

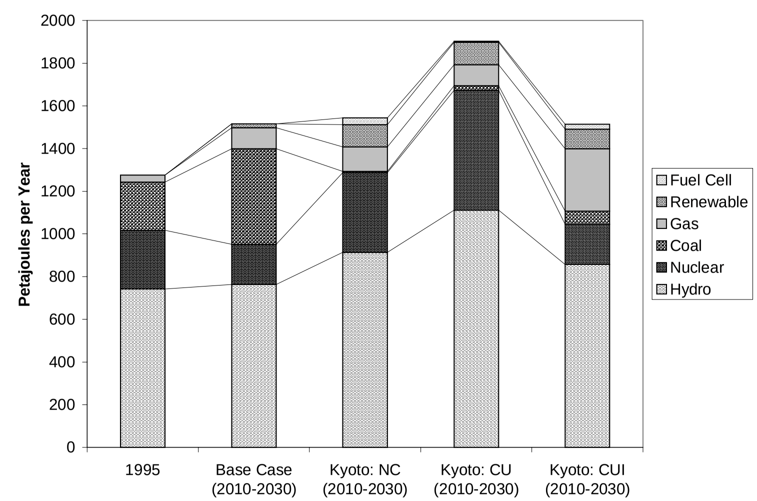

Figure 8 Average Annual Electricity Generation in Canada

Result of 1995

Average result over the 2010-2030 period

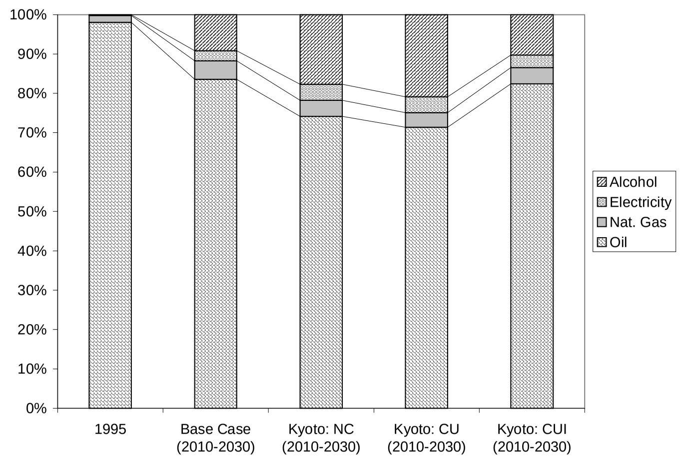

Figure 9 Transport Sector Fuel Composition in Canada[13]

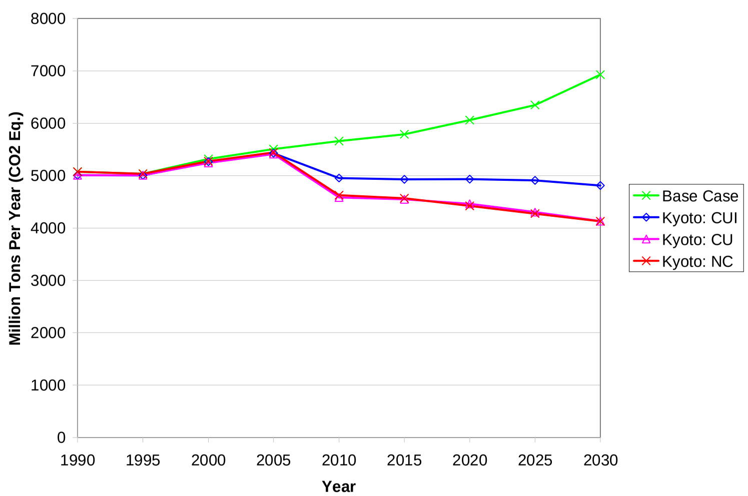

Figure 10 Annual GHG Emission for USA

13 Since Electricity vehicles have much higher efficiency compared to internal combustion vehicles, this figure under-represents the market share of electricity vehicles.

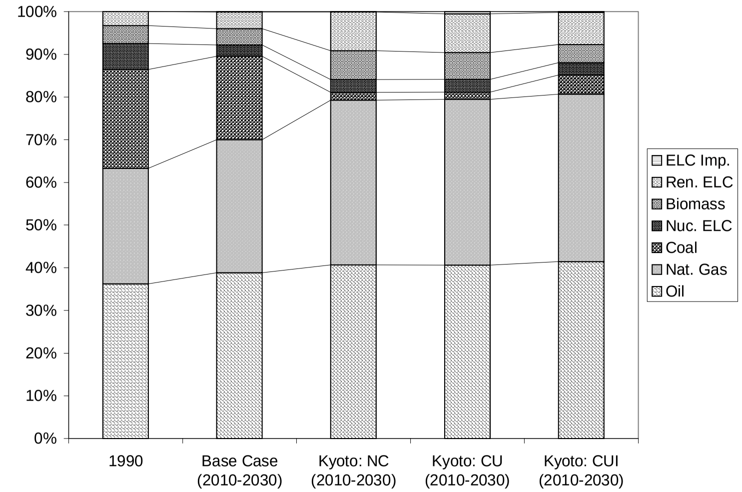

Figure 11 Composition of the Primary Energy Consumption for USA

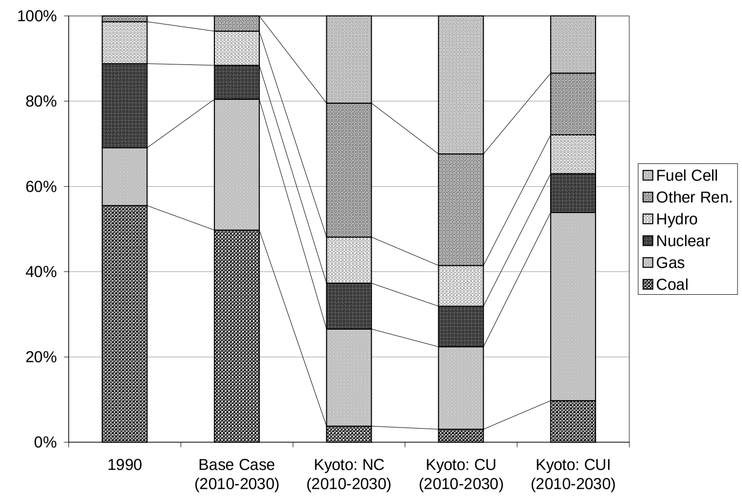

Figure 12 Composition of Electricity Generation in USA

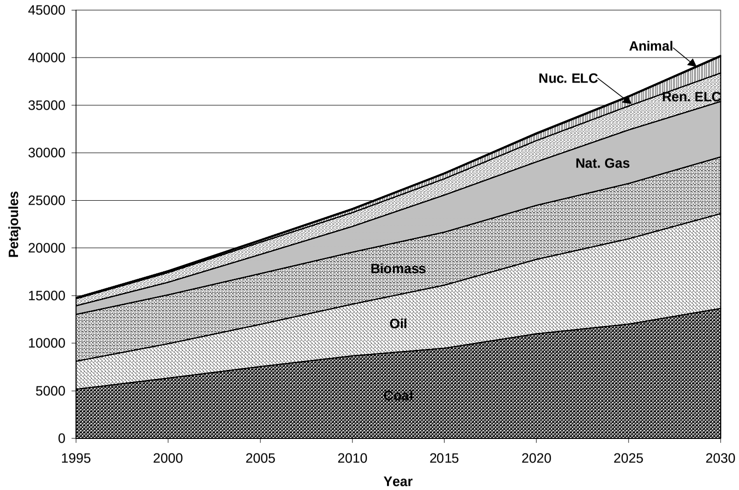

Figure 13 Aggregate Primary Energy Consumption for India (Base Case)

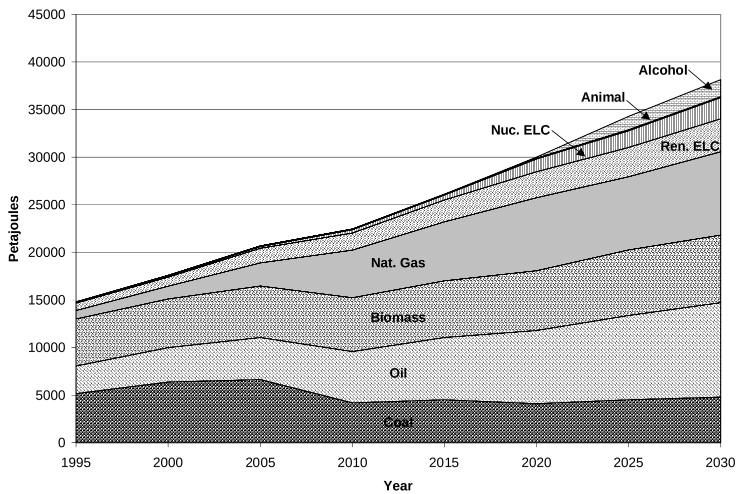

Figure 14 Aggregate Primary Energy Consumption for India (Cooperation with North America)

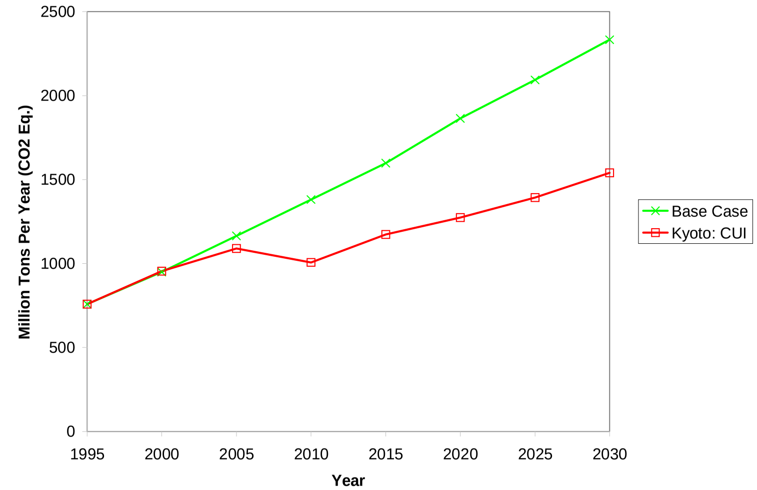

Figure 15 Annual GHG Emission for India

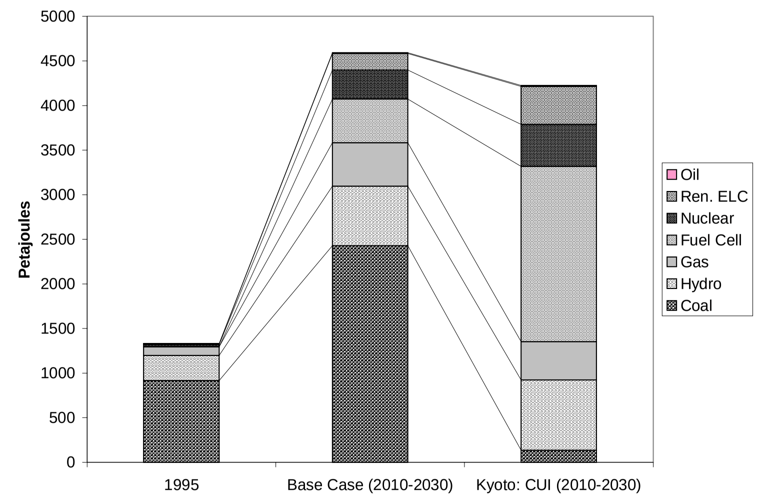

Figure 16 Average Annual Electricity Generation in India