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Nuclear Electricity and Canada's Domestic Response to the Kyoto Protocol: Modeling the Economics of Alternative Scenarios

Computare
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Thoughtful Strategies for Climate Change

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DISCLAIMER

This report was written solely for the purpose of modeling and analyzing a number of scenarios via the MARKAL model. Computare, HALOA INC, and the authors shall not be responsible or liable for any consequences resulting from the interpretation or recommendations made by others based in whole or in part on data presented in this report.

PROLOGUE

During the course of modeling related to the National Climate Change Process, it was noted by representatives of the nuclear industry that the work did not take into account the possible development of lower cost nuclear technology[1]. Issue Table constraints[2] relating to nuclear energy also prevented any uptake of current nuclear technology in the modeling. The pace of the Issue Table and Analysis and Modeling Group work did not permit refinement of the models to accommodate changing the scope of modeling parameters for a single technology[3]. Neil McIlveen, Co-Chair of the Analysis and Modeling Group suggested that an alternative for the nuclear industry would be to independently engage the expertise applied to the analysis process. Parametric surveys could be undertaken to evaluate the potential of nuclear energy on the basis of current and future industry expectations of technology development. The nuclear industry accepted this challenge and engaged HALOA Inc. to supplement[4] the analysis undertaken by the Analysis and Modeling Group. This report presents the results.

ACKNOWLEDGMENTS

Graham Campbell and Neil McIlveen, both of Natural Resources Canada, participated in many discussions and made observations and suggestions that led to this initiative to undertake supplementary analysis building on the effort of the Analysis and Modeling Group. We thank them for that. We particularly appreciate the thoughtful comments provided during the review process and acknowledge Neil McIlveen, Brian Moore, Pierre Guimond, Betty Rozendaal, Jerry Hopwood, Romney Duffey, Sylvana Guindon and Judy Tamm for their contributions. Finally we thank the Canadian Nuclear Association and it's member organizations for their support of this work.

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[1] Pendergast, Duane, Letter to Graham Campbell, Co-Chair, Technology Issue Table, "Technology Advancements and the Analysis and Modeling Group: Incorporation of Learning Curves and Future Cost Projections", March 23, 2000

[2] Pendergast, Duane, and Betty Rozendaal, Letter to David Oulton and John Donner, Co-Chairs, Integrative Group, "Analysis and Modeling: Comments and Recommendations", October 12, 2000.

[3] Campbell, Graham, Letter to Duane Pendergast, June 21, 2000.

[4] Donner, John and David Oulton, Letter to Duane Pendergast and Betty Rozendaal, November 3, 2000

SUMMARY

Canada's National Climate Change Process has undertaken extensive analysis of the implications of implementing the greenhouse gas reduction commitments of the Kyoto Protocol. The results of work undertaken by the Issue Tables are documented on the National Climate Change Process Internet World Wide Web site.

The final reports from the Analysis and Modeling Group have been interpreted by some as evidence that nuclear energy has no role to play in reducing greenhouse gas emissions in Canada as it is uneconomic. Yet nuclear energy is a proven means of generating electricity in Canada that does not emit greenhouse gases and that can be economic under a range of circumstances.

This paper reviews the analysis and modeling work to establish the reasons for this apparent anomaly. It turns out that modeling of nuclear electricity production is highly constrained by some of the modeling input assumptions initiated with the modeling work of the Electricity Table. These constraints were subsequently carried through to modeling of the entire Canadian economy. The constraints are derived from consideration of historical political, social and economic limitations on nuclear energy deployment and development, which may be overcome in a greenhouse gas constrained Canada. These constraints, which were imposed on decision and construction time, are not technical in nature and do not realistically reflect newer technology.

A key modeling scenario is re-evaluated to consider the effect of a shorter decision time and to reflect current nuclear industry capability with respect to construction time. We also take into account revised input parameters to account for a reduced capital cost system which is the goal of the CANDU designer. These changes result in the model choosing more nuclear energy as a least cost source of electricity. The increase in nuclear electricity is substantial for the scenarios that investigate the role of reduced capital cost nuclear power plant systems.

The results demonstrate that nuclear electricity has a legitimate place in the analysis of options for Canada to meet its Kyoto commitment. A relatively modest (compared to fluctuations and changes in energy commodities) cost reduction leads to the model choosing nuclear over other competing technologies thus confirming basic competitiveness. Precluding the selection of nuclear energy in forward looking economic analyses may lead to underestimating its potential as a greenhouse gas reducing energy source for the future. We conclude that future modeling work, which is intended to help guide Canada's course with respect to greenhouse gas reductions should include nuclear technology – and any other relevant technology.
The assumptions about nuclear plant capital costs and decision and construction times included in the original modeling were based on inferences from the history of nuclear development, from then current nuclear energy research, from recognition of the historical timelines and complexities of regulation and from observations of the public ambivalence concerning nuclear power. An alternative but perhaps more realistic and now more timely set of assumptions leads to interesting results, as we demonstrate in this study.

Nuclear Electricity and Canada's Domestic Response to the Kyoto Protocol: Modeling the Economics of Alternative Scenarios

Introduction

Canada's National Climate Change Process has undertaken extensive analysis of the implications of implementing the greenhouse gas reduction commitment of the Kyoto Protocol. The results of work undertaken by the Issue Tables are documented on the National Climate Change Process WWW site[1].

The final reports from the Analysis and Modeling Group[2] (AMG), have been interpreted by some as evidence that nuclear energy has no role to play in reducing greenhouse gas emissions in Canada as it is uneconomic. The reports conclude that nuclear electricity production generally declines to about 70% of 1995 levels by 2010 as shown in Figures 8 & 9[3]. This predicted decline prevails even under economic conditions that provide a substantial economic incentive to generate electricity from greenhouse gas free energy sources. Yet nuclear energy is a proven means of generating electricity in Canada that does not emit greenhouse gases and that can be economic under a range of circumstances.

This paper reviews the analysis and modeling work to establish the reasons for this apparent anomaly. It turns out that modeling of nuclear electricity production is highly constrained by modeling input assumptions initiated with the modeling work of the Electricity Table (ET) and carried through to subsequent modeling of the entire Canadian economy. These constraints are derived from consideration of historical limitations on nuclear energy deployment and development, which may be overcome in a greenhouse gas constrained Canada. For example the input to the economic modeling assumes that no decision to build a new nuclear power plant in Canada could be taken before 2013. It is further assumed that subsequent to a decision to go ahead, it would take ten years to build a nuclear power plant. These two input assumptions alone are sufficient to prevent the deployment of any new nuclear capacity over the study period to 2020. The contribution of nuclear energy is thus limited to a prescribed output from existing nuclear power plants based on Ontario Power Generation data provided to the Electricity Table and applied to the modeling by HALOA in February 1999.

The assumptions on decision and construction time applied by the Electricity Table and provided to the Analysis and Modeling Group are not technical constraints on nuclear electricity. We proceed to repeat a key modeling case to consider the effect of a shorter decision time and to reflect current nuclear industry capability with respect to construction time. We also take into account revised input parameters to account for a reduced capital cost system which is the goal of Atomic Energy of Canada Limited, the CANDU designer. The Canadian Nuclear Association anticipates the revised design will be established for construction around 2005.

The results indicate that removal of the decision and construction time constraints imposed on nuclear electricity does allow the models to choose this option. Introduction of lower capital cost nuclear plants now under development has the potential to help Canada meet Kyoto commitments at a lower cost to Canada than options considered in the analysis undertaken by the National Climate Change Process.

The assumptions about nuclear plant capital costs and decision and construction times included in the original modeling were based on inferences from the history of nuclear development, from then current nuclear energy research, from recognition of the historical timelines and complexities of regulation and from observations of the public ambivalence concerning nuclear power. An alternative but perhaps more realistic and now more timely set of assumptions leads to interesting results, as we demonstrate in this study.

Analysis and Modeling Background

This section describes the original modeling work undertaken by the National Climate Change Process. It was a long and complex process involving input from hundreds of individuals and scores of organizations. Definition of input to the modeling began with the fifteen plus Issue Tables. The Issue Tables initially defined an overview of the status of greenhouse gas emissions from the full range of economic sectors. The Tables then proceeded to define policy options deemed best suited to effecting greenhouse gas reductions in their sectors. The Analysis and Modeling Group (AMG) sought input from the sector Issue Tables as a basis for initiating an integration of the sectors. Attention was initially focused on micro modeling that essentially assumes that the overall Canadian economy develops and grows according to predefined parameters established prior to and outside the model. The modeling culminated with macro modeling which evaluated feedback effects on the Canadian economy from greenhouse gas reduction initiatives. The Electricity Issue Table undertook early modeling and established many parameters that ultimately defined the role of electricity in the overall models.

This study, which focuses on parametric variations in nuclear electricity input assumptions, otherwise relies completely on analyses established by the Electricity Table[4] (ET) and the Analysis and Modeling Groups (AMG) micro-modeling[5] based on the use of the Market Allocation (MARKAL) model. The AMG also undertook parallel micro modeling based on the Canadian Integrated Modeling System (CIMS) model. Since that analysis depended to a large extent on the modeling of electricity from the MARKAL model, it was decided to use only the MARKAL model for the present re-analysis. The macro modeling work is also ignored by this reanalysis, as it is dependent on micro-modeling input with respect to nuclear electricity production.

The computer software model, MARKAL was developed by a cooperative multinational project over a period of almost two decades by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency. The basic components in a MARKAL model are specific types of energy or emission control technology. Each is represented quantitatively by a set of performance and cost characteristics. The model selects the combination of technologies that minimizes total energy system cost. Its application by the government of Canada to the analysis undertaken by the AMG is summarized in a recent article[6], co-authored by two of us (Loulou and Kanudia), in the ETSAP newsletter.

Although it is impossible to document all of the relevant MARKAL model input information in this paper some information on costs of producing electricity from different technologies is of particular relevance. The investment cost is especially important. The ET established these costs mostly on the basis of public domain information. Cost estimates for hydroelectric facilities were obtained from Canadian utilities and were deemed proprietary. A preliminary study commissioned by the ET[7] provided an estimate, which indicates hydro electricity facilities in Canada would range from $1500 to $2500/per kW of installed capacity. Figure 1 shows investment cost input to the MARKAL model (from HALOA's input data files) and the estimated high and low investment costs for hydroelectric facilities in 1990 Canadian dollars per kW of installed capacity. High capital cost technology with a long construction time is particularly sensitive to capital cost and discount rates. The MARKAL micro-modeling reference analysis is based on a discount rate[8] of 10%. Figure 1 shows differing capital cost per kW installed capacity with time for some technologies. These variations represent an estimate of expectations for reductions due to improvements in technology with time. Figure 2 shows additional details for reduced capital cost of renewable technologies. These reflect a projection that there is potential for dramatic reductions in the cost of photovoltaic electricity production whereas solar thermal electricity production and wind power technology may be approaching maturity. Figure 2 shows a decrease from $1125 to $825 per kW installed capacity for wind power over the study time period. In addition to the investment cost the ET developed input data to the MARKAL model to reflect fixed and variable operating costs including fuel costs where applicable, as well as all technical parameters for each technology.

Geological sequestration of carbon dioxide emissions was introduced into the modeling data. Cost and capacity estimates for two variations of this developing technology were established and used in the model. Sequestration was limited to provinces with appropriate geological structures. The ET Options Report[9] and the reference micro modeling analyses[10] indicate that a small amount of sequestration (1.5 Mt/year) at $13/tonne CO2 from enhanced oil recovery was allowed. Sequestration in aquifers was also available in unlimited quantities at $38/tonne CO2.

As previously mentioned new nuclear capacity was precluded, by modeling input assumptions, prior to 2020 in the main scenarios studied for the Electricity Table and the Analysis and Modeling Group.

The Analysis and Modeling work was initially carefully structured to provide a reference to "Business as Usual" as defined by NRCan's Energy Outlook 2020[11] and to integrate the recommendations of the many "Issue Tables" (Path 0). More general solutions were then sought to evaluate the impact of the Kyoto GHG reduction commitment on economic sectors (Path 1), on the economy as a whole (Path 2), to impose a cap and trade system on just the large emitters (Path 3) and then to impose a cap and trade system on about 75% of the Canadian economy (Path 4). These five basic analysis "Paths" presume that Canada acts alone and independently from other nations to meet the Kyoto commitment.

Four additional scenarios were undertaken in the original modeling work to evaluate the effect of international emission credit trading. These analyses are based on information established by analysis of modeling work undertaken in the United States[12]. The US modelers established several scenarios to evaluate the role international emissions trading might play in reducing costs to the US economy relative to strictly internal compliance with the Kyoto commitment. These studies established a price for internationally traded emissions credits. The AMG selected two of these, which bounded a reasonable range, and dubbed them the "Kyoto Tight" and "Kyoto Loose" scenarios.

One US result chosen for analysis by the AMG concluded that an international CO2 emissions trading price of C$60/tonne in 2010 would result in closing 2/3 of the US Kyoto gap by reductions within the US. This result was called the "Kyoto Tight" scenario within the AMG. The other case chosen by AMG indicated that an international trading price of C$25/tonne in 2010 would require only a 25% reduction of the US gap through internal actions. This result was called the "Kyoto Loose" scenario. The analysis provides an indication of the role international CO2 trading prices would have on US domestic emission reductions.

The AMG postulated that, since the Canadian economy is closely linked to that of the US, that the emission trading prices established by the US study would also be appropriate to the assessment of international emissions trading on the Canadian economy and emissions estimates. The AMG then undertook four more modeling scenarios by superimposing the "Kyoto Tight" and "Kyoto Loose" CO2 emission trading prices on Path's 2 and 4. Under these modeling scenarios Canada is allowed to buy emissions credits internationally. All nine scenarios are described in considerable detail in the AMG modeling report[13].

The results of the analysis indicate that the amount of nuclear electricity produced under all nine scenarios does not vary from scenario to scenario. Comparison of Figures 8 & 9, based on the reference AMG analysis, illustrate this invariance. This is expected as existing nuclear power plant output is prescribed[14] and new plants are not allowed by the input assumptions.

The Path 2 scenario of the original AMG work is of particular interest as the model is set free to choose the least cost options to meet Canada's Kyoto target. Emissions from the electricity sector are decreased dramatically (a 77.5% reduction relative to 1990) in this path. The reductions are accomplished by reducing fossil fuel production, increasing production of renewable energy (hydroelectric and wind power), and by sequestering 43 Mt/year[15] carbon dioxide from coal plants in Alberta and Saskatchewan. Substantial quantities of hydro electricity are transferred from Manitoba and Quebec to Ontario. Overall electricity production is also reduced by nearly 10% in Path 2 through reduced end use demand. Further discussion of electricity production predictions is available from the Analysis and Modeling Group final report[16]. These predictions indicate production of electricity from natural gas plays a smaller role than anticipated by the wisdom of the last decade.

Current and Future Economic Modeling Parameters for Nuclear Electricity

Many Canadian provinces are currently moving to "deregulate" the production of electricity. The goal is to introduce competition into their electricity production and marketing. Alberta is already well along the road to deregulation. Ontario is introducing changes, which may result in private industry taking control of the operation of nuclear plants in Canada. Changes underway in North America may result in greater sharing of electricity production facilities through increased export of electricity between provinces and between Canada and the United States. Deregulation is thus introducing changes which complicate the prediction of economic assumptions and inputs and could very well render obsolete the modeling input relating to nuclear electricity production. It is conceivable that price changes brought about by these opportunities will create an environment that would lead to entrepreneurial interest in developing nuclear facilities.

The costs of fossil fuel energy to produce electricity are also fluctuating widely. For example the price of natural gas to consumers in southern Alberta for the winter of 2000 has risen to $C6.50/ GJ[17]. This is more than twice the price of $C2.92 for the winter of 1999. The analysis and modeling work establishes a natural gas cost, in Alberta, of about $C2.50/GJ in 2010 without any CO2 charges[18]. However, it is not the goal of this study to reevaluate uncertainties in the availability and price of fossil fuels and we anticipate that others will be investigating the consequences of changes in these input parameters.

The goal of this study is to establish the consequences of revising the constraints that prevented the MARKAL model from choosing nuclear energy as an electricity source. A shorter decision time and the current nuclear industry capability of shorter construction time are used in the model. The effect of a reduced capital cost CANDU system that is to be designed and available for construction by about 2005 is also considered.

The MARKAL techno-economic model includes the concept of a "start" and "lag" time for the introduction of new electricity generation capacity. The "start" time is defined as the earliest time at which a decision could be made to go ahead with a particular generation technology. This parameter is loosely defined and could presumably take into account the time for regulatory and environmental approvals and decisions with respect to financing. The "lag" time is defined as the time required for constructing a power plant and putting it into service once a decision to go ahead has been made. For electricity generation technologies other than nuclear and large scale hydro projects this time was taken to be essentially negligible with respect to the time increments taken by the model and was thus set to zero. Available historical data, and input from utilities, suggested that these times might be significant with respect to any decision to invest in and deploy nuclear and hydro generation technology. The establishment of modeling input data included a pre-judgment by the ET that social and economic considerations would delay any decision to build new nuclear power plants till a "start" time of 2013 and that an additional ten years "lag" would be required to put them into service in any of Canada's provinces. These were the basic input assumptions that prevented new nuclear plants from being chosen as greenhouse gas mitigation technology in the model.

In view of the major changes taking place in Canada's energy and electricity industries, we postulate that it is conceivable economic conditions may develop, possibly very rapidly, which would encourage deployment of new nuclear power plants. Possibly alternative (to nuclear), energy sources may be subject to substantial price increases, beyond those anticipated by the AMG modeling, as well as surcharges resulting from regulations to suppress greenhouse gas emissions. We note that the ET has recommended preparatory measures[19] with respect to large-scale hydro and nuclear energy that would allow decisions to build new capacity to be taken more expeditiously. These include improvements to regulatory efficiency. We thus take the liberty to anticipate that favorable social and economic conditions may develop for nuclear technology in as little as two years. We assign a "start" time for new nuclear generation of 2002, based on established designs, as an input assumption. Atomic Energy of Canada's (AECL) recent experience[20] with

CANDU nuclear plant construction in Korea[21] confirms that, from groundbreaking till in-service, they can be built in less than five years[22] corresponding to a model input "lag" time of five years.

The costs for nuclear electricity used in the modeling done by the ET and subsequent National Climate Change Process economic analyses were based on a study reported[23] by the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD) and the International Energy Agency. AECL has begun design work for a new CANDU system, referred to as NG CANDU[24,25], for next generation, which has a goal to lower capital costs by 30% relative to current systems. The capital cost improvement anticipated is achieved by using uranium fuel enriched in the fissile component of the natural uranium that has fueled CANDU power plants to date. This reduces the size of the reactor and the inventory of heavy water and thus construction cost. The NG CANDU system makes much use of known CANDU technology and is thus anticipated to be ready for construction about 2005. We note that additional development activity[26] is being undertaken by AECL that is expected to reduce CANDU capital costs still further. These potential new designs require long-term development of new fuel channel concepts, however, and are not expected to be ready for construction in the early part of the study period following 2005. We have not taken any credit for these additional improvements during the study time period to 2020. These additional improvements would be most significant to studies extending beyond 2020.

The cost of building and operating CANDU facilities is reviewed in Appendix A to establish the input parameters to MARKAL needed for our study. Changes from the input to MARKAL turn out to be very simple. The capital cost of the new NG CANDU is simply reduced 30% relative to the cost used in the original ET and Analysis and Modeling Group work. Operating costs as a result of incorporating enrichment are evaluated. Although we expect lowered operating costs, this is not significant relative to the cost of capital, and we take operating costs to be the same as for the current CANDU technology for the sake of simplicity and conservatism. Since the NG CANDU plants use similar but fewer components than current CANDU plants we also assume a five year construction period although shorter construction times are also a goal of new designs. Thus the only additional change applied to the modeling for the new NG CANDU design is the reduced capital cost.

Analysis and Modeling Group Reference Case Selection

We noted above, in "Analysis and Modeling Background" that Path 2 seemed of particular interest. That path was designed to achieve the Kyoto goal with the model free to choose the least cost options. Path 2 resulted in a very substantial reduction of emissions from the electricity production sector. This reduction was achieved primarily by increasing the production of hydroelectricity and by sequestering carbon dioxide from coal based electricity at a cost of $C38 per tonne C02. The increased production from these sources was facilitated by increases in inter-provincial electricity trade.

We thus choose Path 2 as the reference scenario to explore the potential for electricity generation from new nuclear power plants. We define variations from the reference Path 2 as "Cases" in this paper in order to distinguish them from the nine AMG "Paths". We have defined four new Cases to evaluate the potential role of nuclear energy under different assumptions.

The first case (Case 1) repeats the analysis as undertaken by the AMG, using current CANDU technology, but changes the "start" time for new nuclear to 2002 with a "lag" time of five years. New nuclear electricity output could be expected as early as 2007 in this scenario due to smoothing approximations of the MARKAL model.

Our second case (Case 2) considers the effect of reducing the investment cost for new nuclear plants by 30% as discussed above for the NG CANDU design. Since the design will not be completed until 2005, we assume a decision to start construction in 2005 could be made. Again a construction time of five years is consistent with current practice so that the effects of lowered capital cost nuclear generation could be expected in the model output by 2010. New CANDU plants using current technology are not included in this scenario.

Case 1 and Case 2 preclude interaction with other nations since Canada is assumed to act alone under Path 2 to meet the Kyoto commitment. This restraint was relaxed in the international scenarios of the AMG studies to take into account the effect of international emissions trading through the imposition of a “shadow price” on CO2 emissions. The export price of electricity is increased in the AMG micro modeling[27] relative to business as usual as an approximation to the increased infrastructure costs anticipated to provide for export capability. The results for Path 2 – Kyoto Tight are particularly interesting. These results indicate maximum exports of electricity to the United States totaling about 20 TWh/year would ensue under that scenario, mainly from hydroelectricity. We thus chose to evaluate the potential role of nuclear electricity in that export scenario by repeating the analyses of Case1 and Case 2 with the Kyoto Tight conditions (Emissions trading internationally at $C 60/tonne allowed) applied. These constitute our Case 3 and Case 4, respectively.

We have applied one additional constraint to the production of nuclear generated electricity for Cases 3 and 4. We were concerned that the model might leap to extremely large exports of electricity to the US from new nuclear plants that would overwhelm any real capability of Canadian industry to supply the needed infrastructure. The Canadian economy is not likely large enough to supply human and technical resources needed to satisfy the US market. We thus chose to limit exports to the US so that they come only from those provinces now actively exporting to the US and we limited their export capacity to 10% of their domestic electricity consumption. We left the other provinces free to export electricity to the provinces that currently export to the US. These constraints were chosen to reveal any trend toward construction of new nuclear plant for export purposes while maintaining some consistency with present electricity trade patterns. This precaution turned out to be unnecessary, as the model did not confirm the anticipated large trades.

The results for the reference AMG micro-modeling were reported only up to 2010 although all of the analyses were completed to 2020. We extend the reported results for electricity for the reference Path 2 case to 2020. The results of all four new Cases defined herein are also reported to 2020 in order to evaluate more completely the potential longer-term contribution of new nuclear plants in Canada. Table 1 summarizes the variations from the reference micro-modeling analysis introduced to evaluate the role of nuclear electricity with constraints representing current technical capability.

Table 1 – Nuclear Electricity Modeling Input Assumptions

Scenario	**Start Time (Year)**	**Lag Time (Years)**	**Nuclear Technology**	**Trading of CO2 Emission Credits Outside Canada**
Reference Analysis (AMG Path 2)	2013	10	Existing nuclear stations plus new CANDU 6	No
Case 1	2002	5	Existing nuclear stations plus new CANDU 6	No
Case 2	2005	5	Existing nuclear stations plus new NG CANDU	No
Case 3	2002	5	Existing nuclear stations plus new CANDU 6	Yes
Case 4	2005	5	Existing nuclear stations plus new NG CANDU	Yes

Results and Discussion

The output from MARKAL is massive. Figures 3 to 18 provided at the end of this report summarize the model results of primary interest. The figures include information on electricity generating capacity, electricity production, GHG emissions, timing of decisions to install new nuclear capacity, and exports of electricity under various scenarios. A discussion follows of the main points established by the analysis and illustrated by reference to the Figures.

Case 1, based on current CANDU 6 costs with start and lag time constraints revised as indicated above resulted in installation of new nuclear plants with about 1.5 GW (~ 2 CANDU 6 plants) of new capacity started in Ontario in 2010 (See Figure 15). The economics of this scenario favors new nuclear plants only in Ontario. Case 1 demonstrates that nuclear electricity is a contender on an economic basis under the revised assumptions.

Case 2, based on NG CANDU capital costs (*The CANDU 6 is not an option in this Case*.) with a decision time set to 2005 and a construction period of five years indicates that Canada would install about 16.5 GW of new nuclear capacity. This totals about 24 new nuclear plants, each of 665 MW capacity, operating by 2020. Figure 16 shows that decisions to build these plants begin in 2005 and carry through to 2015. The number of plants predicted are seven for Alberta, two for Saskatchewan, twelve for Ontario and three for New Brunswick and Nova Scotia. The growth in nuclear capacity and production are shown in Figures 5 and 10, respectively. The nuclear plants displace fossil fuel (mainly coal) as can be seen from Figures 9 and 10. Hydro electricity exports from Quebec and Manitoba to Ontario in the corresponding AMG Path 2 scenario are also reduced. Interestingly, GHG emissions from the electricity sector are barely reduced from the "Canada Acts Alone Path 2" scenario of the AMG work. This is because emissions are already very low, as emissions from coal-fired plants are sequestered and the lower cost nuclear plants displace production from this and GHG free technology. Nuclear power using NG CANDU would be competitive, at a GHG sequestration cost of $38 per tonne C02, and would provide the low-cost route to meeting the Kyoto commitments (although not quite to the Kyoto schedule).

We had anticipated that the Path 2 "Kyoto Tight" variations of Cases 3 and 4 might lead to the installation of nuclear plants in Canada for the export of electricity to the United States. However the changes from Case 1 and 2 were not in that direction. In fact no new nuclear plants were installed in Case 3 (compared to 1.5GW in Case 1). Case 4 conditions resulted in the installation of fewer new nuclear plants than Case 2 where Canada achieves the Kyoto goal without emission trading. Six new NG CANDU power plants were called for (compared with 24 plants in Case 2) with approximately 2 each in the Prairie Provinces, Ontario, and the Atlantic Provinces. Figure 17 shows the decisions to install new nuclear capacity in each region as well as the magnitude of new capacity.

In both Cases 3 and 4, it was cheaper for Canada to buy emission credits abroad. Comparison of the detailed results for these two cases revealed that the internal trading prices for CO2 emissions established by the MARKAL model were higher in Case 2 than the trading price of CO2 emissions set by the Kyoto Tight constraint of Cases 3 and 4. Canada thus achieved part of its emission reductions by buying lower cost credits. Canada's actual emissions from electricity production are higher for Case 4 than for Case 2, in 2020, where Canada is constrained to reach GHG reduction commitments internally. Figure 14 shows the magnitude of this increase. Thus to the extent that Canada wishes to meet a high proportion of its reduction commitments internally, Cases 3 and 4 would not be an acceptable scenario.

The MARKAL model provides an indication of overall cost to Canada from the various scenarios. The reference analysis, Path 2, estimated the present value of costs to Canada at 14 billion dollars[28] over a 20 year period compared to the business as usual case. Case 2, with the installation of 24 new reactors indicated an overall saving of about 1.5 billion dollars over the 20 year period relative to the Path 2 reference case. Offhand this seems insignificant in the context of the entire Canadian economy. However this value is expressed as the net present value in 2000, in 1995 Canadian dollars. The discount rate of 10% greatly reduces the savings incurred past 2010 realized by the production from the new nuclear plants. If the same cost savings were discounted to 2008, approximating the time the plants would be built, rather then 2000 they would then have a net present value of 3.2 billion (1995 C$).

Conclusions

Analyses undertaken by the Analysis and Modeling Group have been taken as the starting point for a study of variations in nuclear electricity parameters. The new analyses indicated that with the removal of constraints that prevented the original AMG models from choosing new nuclear plants using existing CANDU technology, some installation of new nuclear capacity resulted. This suggests that the cost of current nuclear plants designs is in the "ball park" with respect to competing with other GHG free alternatives.

The introduction of a 30% reduction in the cost of new nuclear plants resulted in the MARKAL model indicating installation of a large amount of new nuclear capacity as a cost effective alternative. A cost variation of this magnitude is modest in comparison with possible variations and unknowns in total electricity production cost – up or down – of competing modes of electricity production and distribution. For example, current escalation in the natural gas price will increase the price of electricity from that source by well over 30%. We also note that the AMG "Path 2" analysis predicted substantial exports of hydro electricity from producing to consuming provinces and the sequestration of emissions from coal plants. Uncertainties in the cost of infrastructure to implement those alternatives may also be significant relative to the CANDU capital cost reduction introduced in this analysis.

These results should not be taken as a clear indication that Canada will, or should, rush to install a large number of new nuclear plants. Existing nuclear plants may well be encouraged (i.e. life extension - note that the original AMG assumptions with respect to Bruce A[29] may already be subject to change.) to produce more electricity than they are credited for in the analysis. There are many technical uncertainties in the modeling as well as uncertainties associated with the costs of fuels and new technology noted above.

The results do demonstrate that nuclear electricity has a legitimate place in the analysis of options for Canada to meet its Kyoto commitment. A relatively modest cost reduction leads to the model choosing nuclear over other competing technologies. Its basic competitiveness is thus confirmed. In a number of cases, nuclear power seems to be the most cost-effective way of meeting the Kyoto commitments and electricity demand through domestic initiatives. The same conclusion would presumably hold for initiatives to meet further reductions in emissions post-Kyoto.

Precluding the selection of nuclear energy in forward looking economic analyses may lead to underestimating its potential as a greenhouse gas reducing energy source for the future. We conclude that future modeling work, which is intended to help guide Canada's course with respect to greenhouse gas reductions, should include nuclear technology – and any other relevant technology. The assumptions about nuclear plant capital costs and decision and construction times included in the original modeling were based on inferences from the history of nuclear development, from then current nuclear energy research, from recognition of the historical timelines and complexities of regulation and from observations of the public ambivalence concerning nuclear power. An alternative but perhaps more realistic and now more timely set of assumptions leads to interesting results, as we have demonstrated in this study.

Figure 1 - Generating Plant Investment Costs

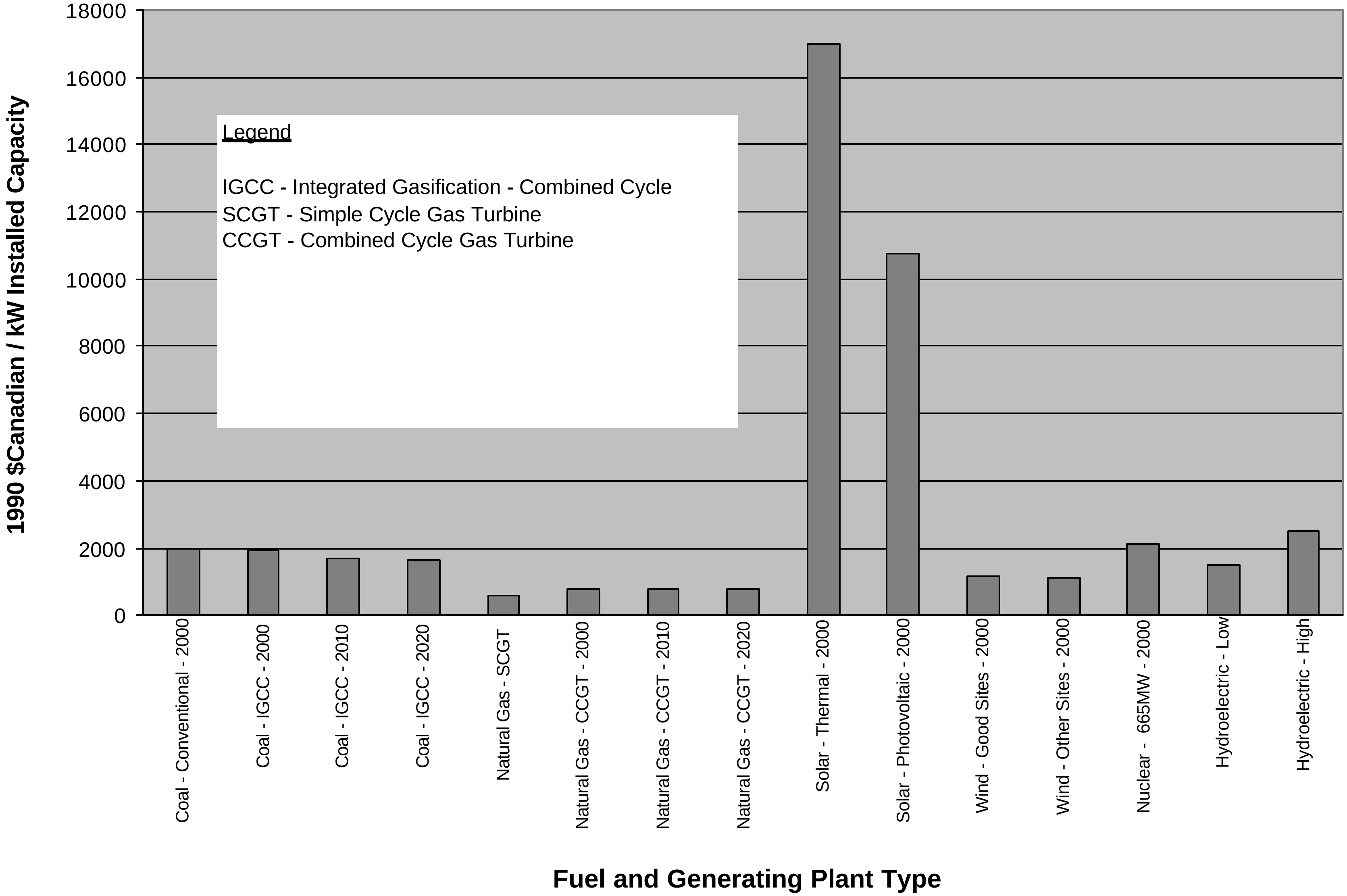


Figure 2 -" Emerging" Technology Investment Costs

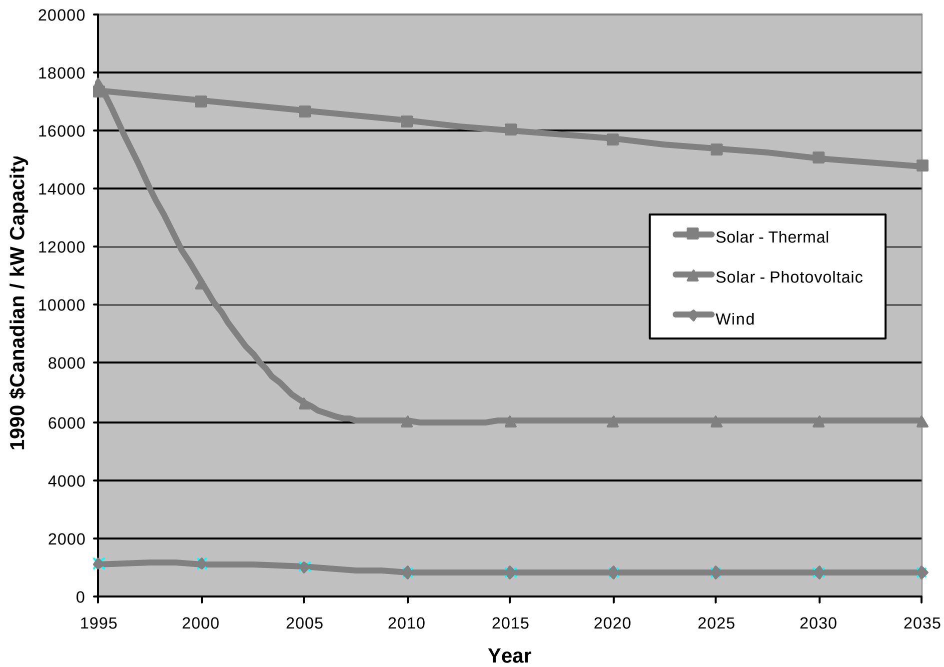


Figure 3 - Electricity Capacity - AMG Business as Usual

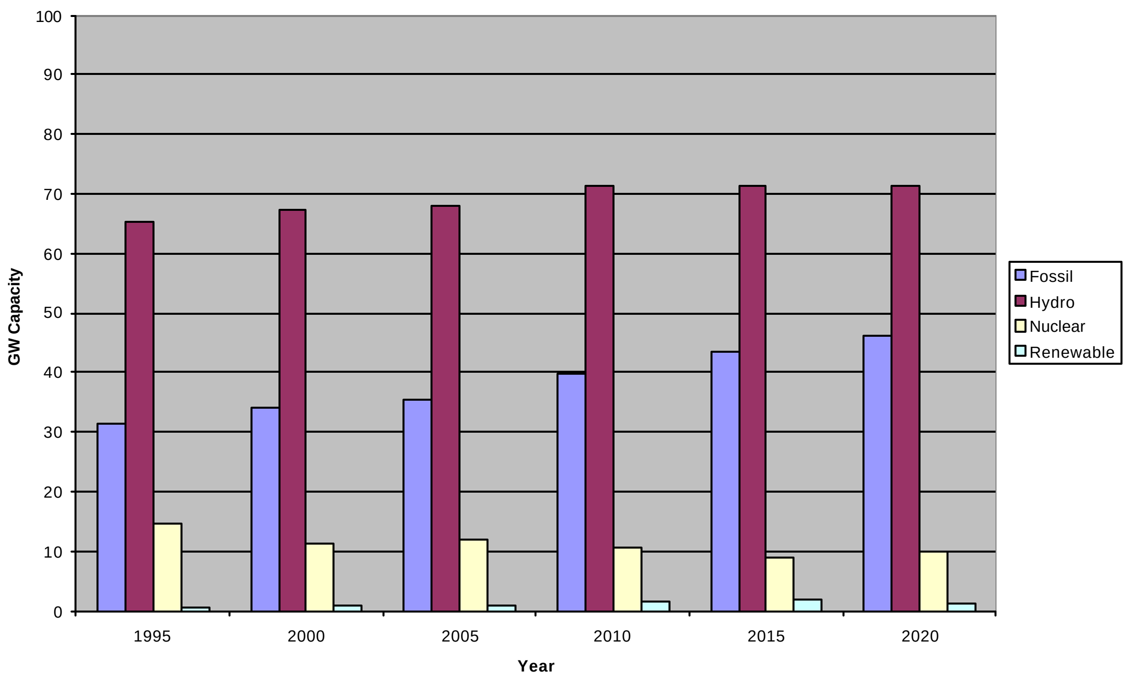


Figure 4 - Electricity Capacity - Canada Acts Alone - AMG "Path 2"

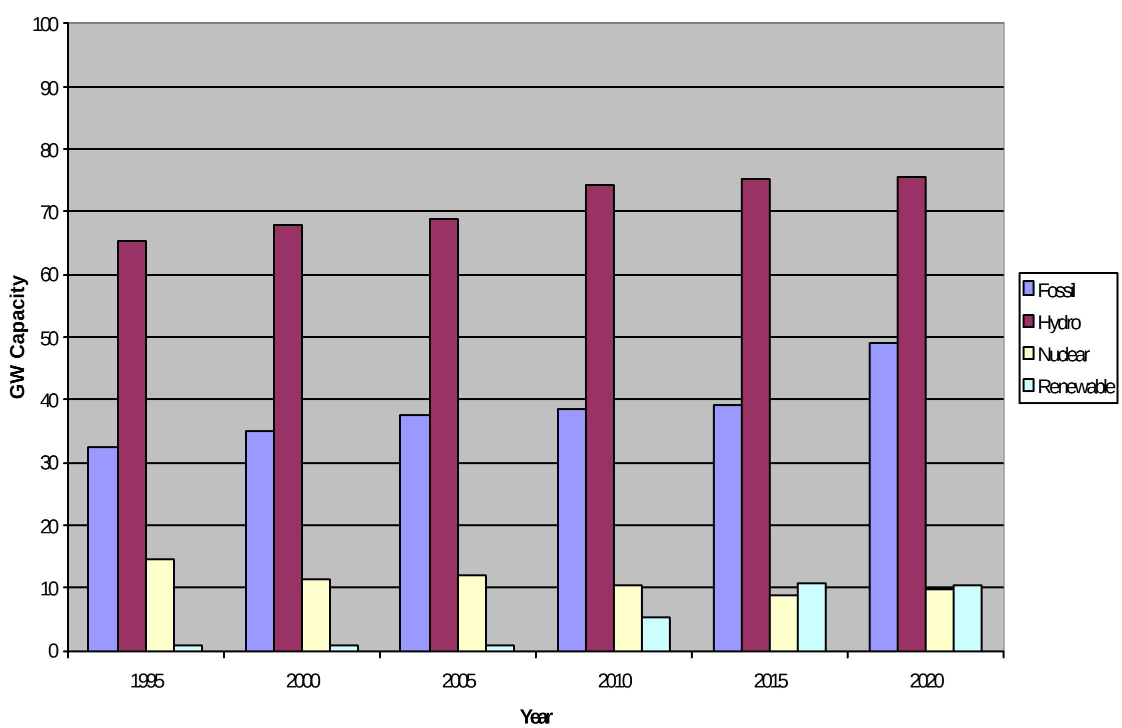


Figure 5 - Electricity Capacity - Canada Acts Alone with CANDU NG (Case 2)

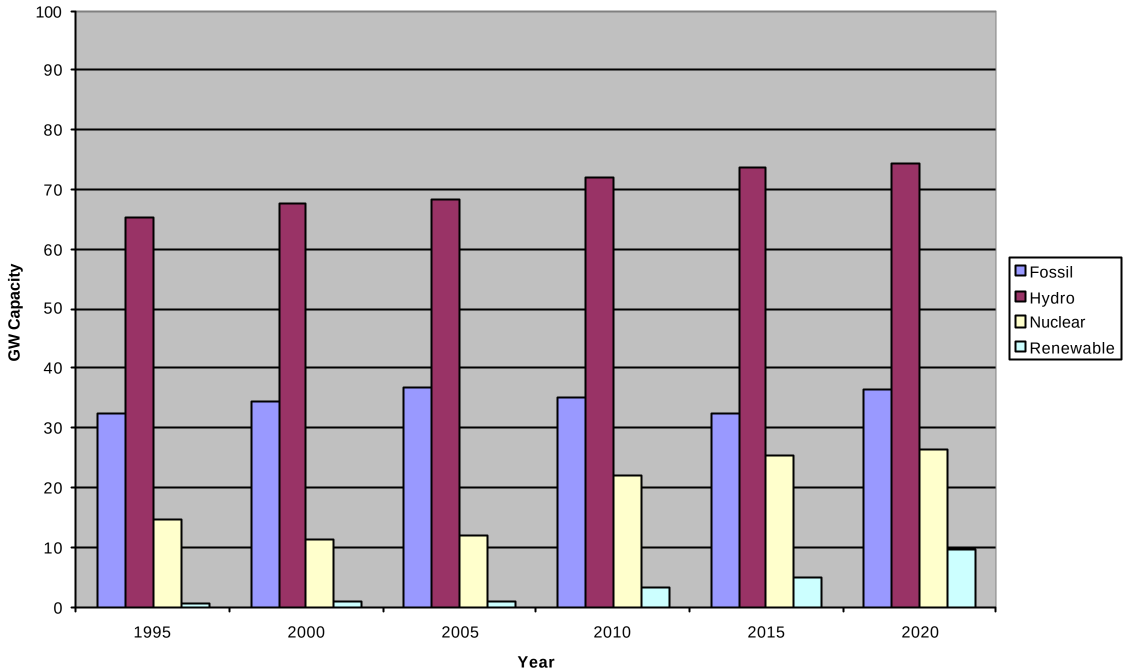


Figure 6 - Electricity Capacity - International Emissions Trading - AMG Path 2 - Kyoto Tight

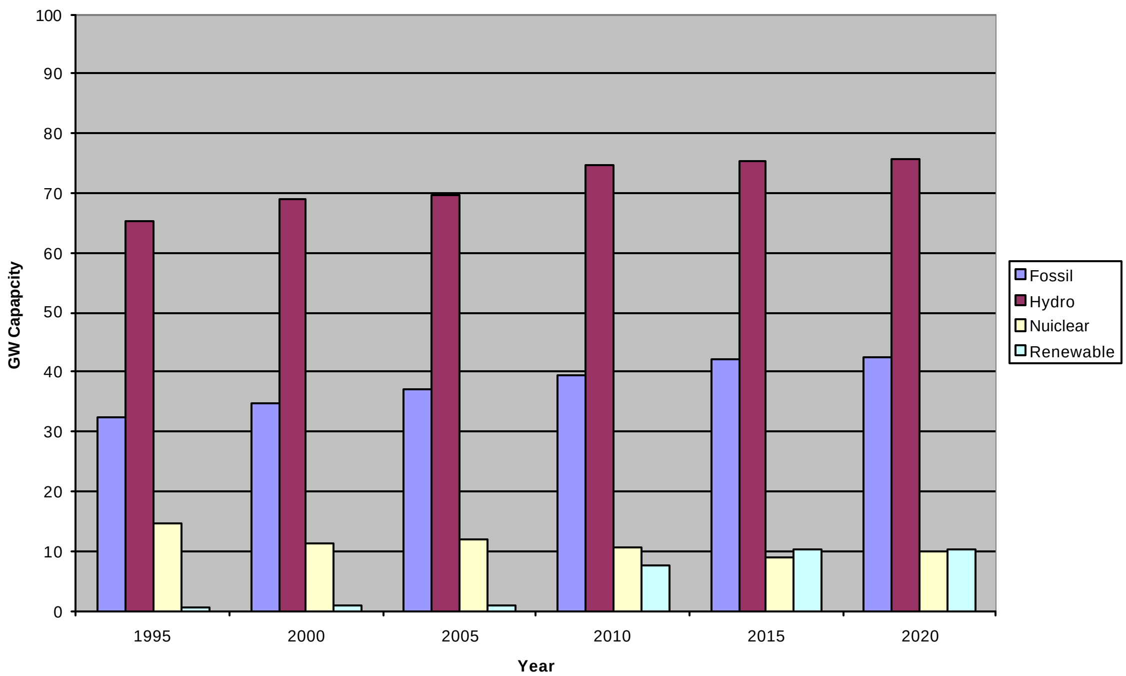


Figure 7 - Electricity Capacity - International Emissions Trading - CANDU NG - "Kyoto Tight" (Case 4)

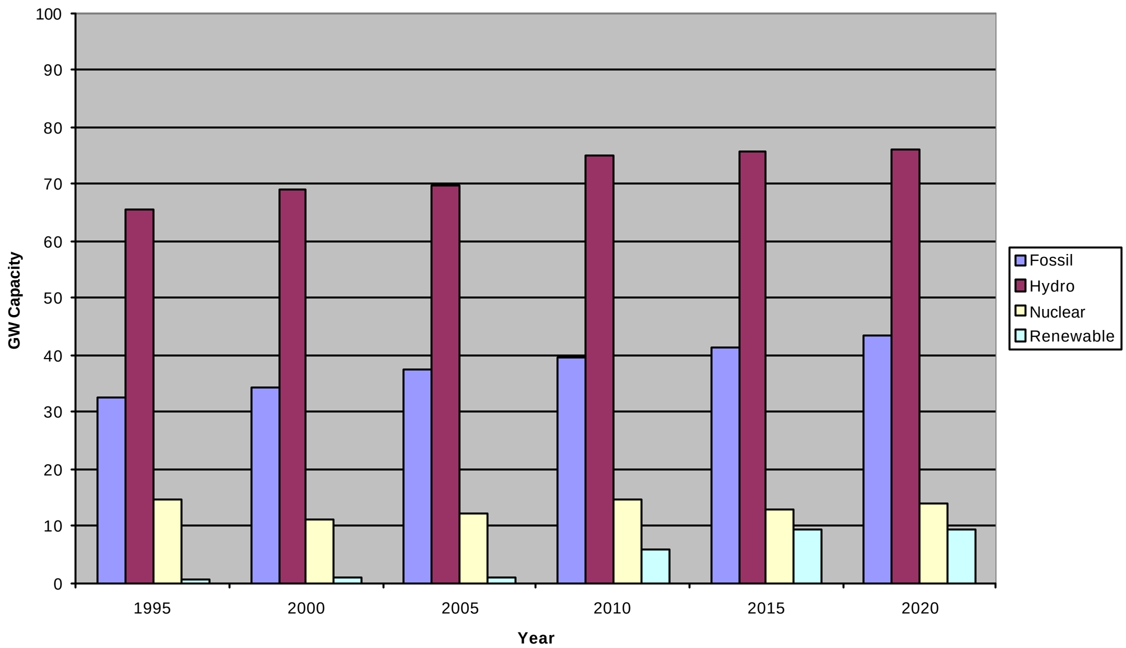


Figure 8 - Electricity Production - AMG Business as Usual

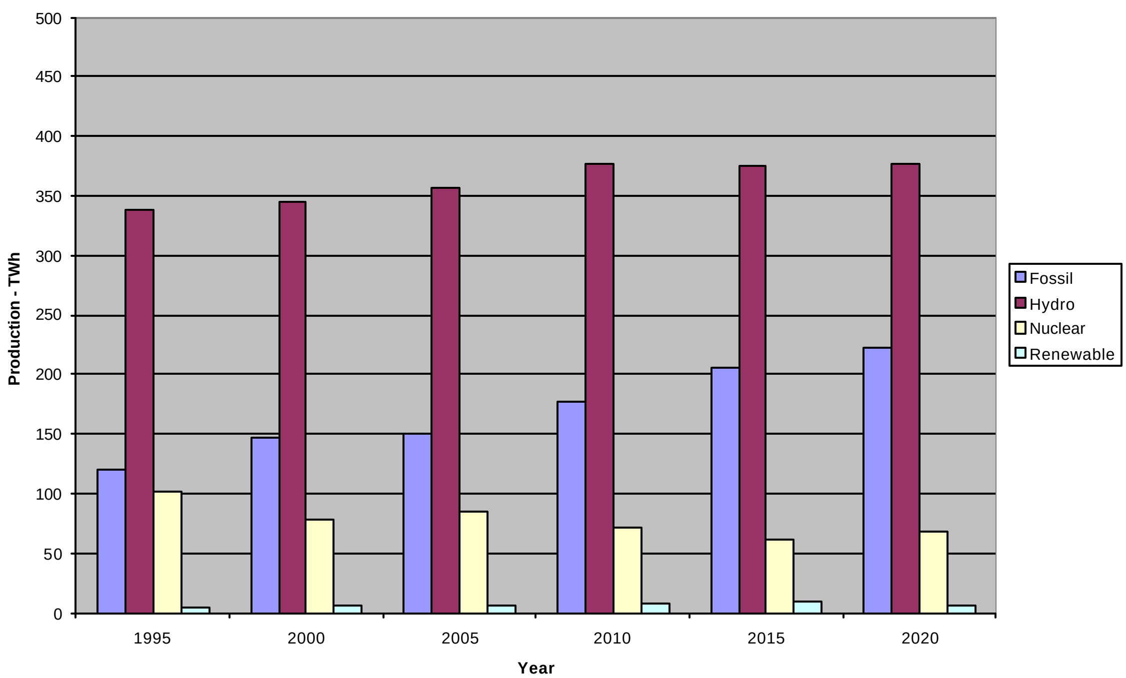


Figure 9 - Electricity Production - Canada Acts Alone - AMG "Path 2"

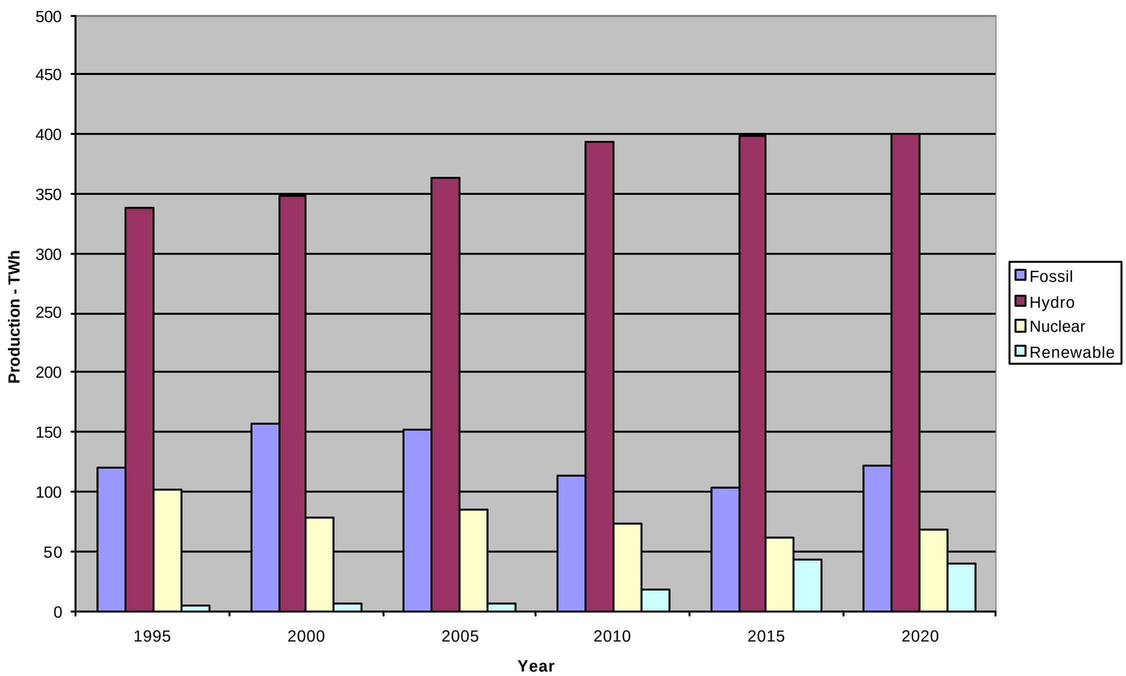


Figure 10 - Electricity Production - Canada Acts Alone with CANDU NG (Case 2)

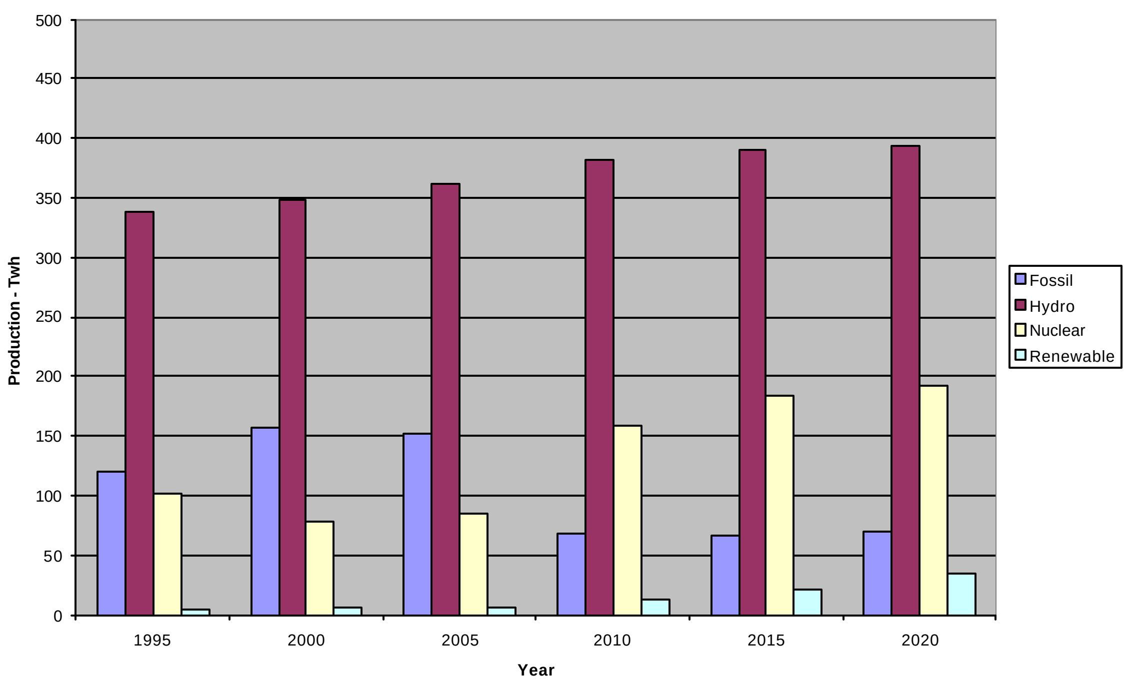


Figure 11 - Electricity Production - International Emissions Trading - AMG Path 2 "Kyoto Tight"

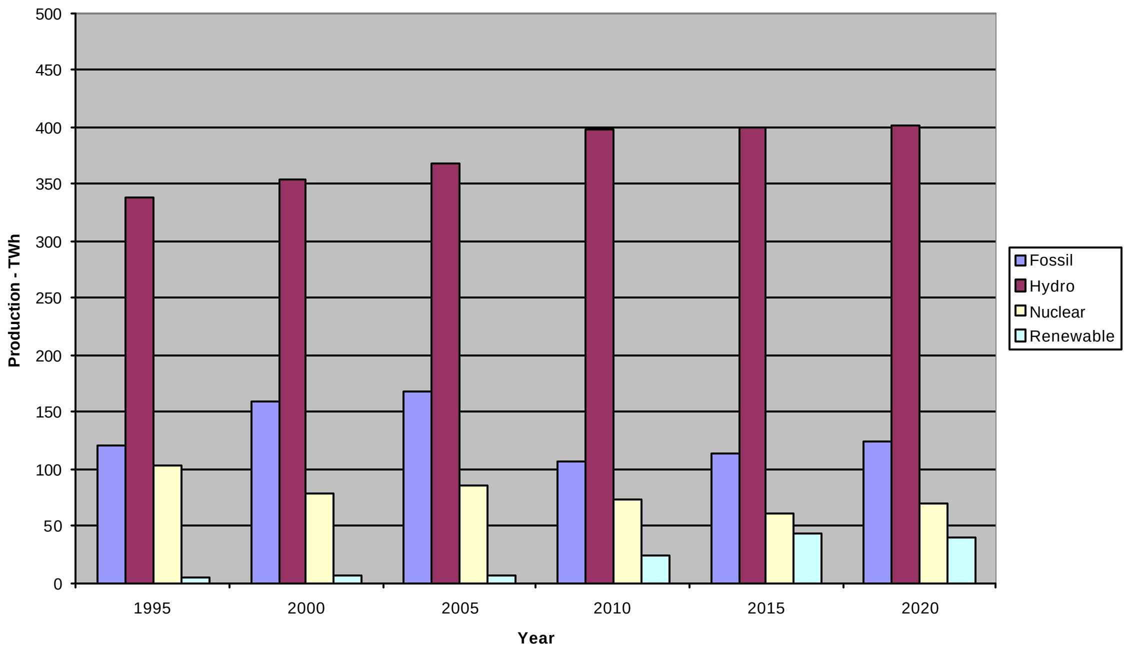


Figure 12 - Electricity Production - International Emissions Trading - CANDU NG "Kyoto Tight" (Case 4)

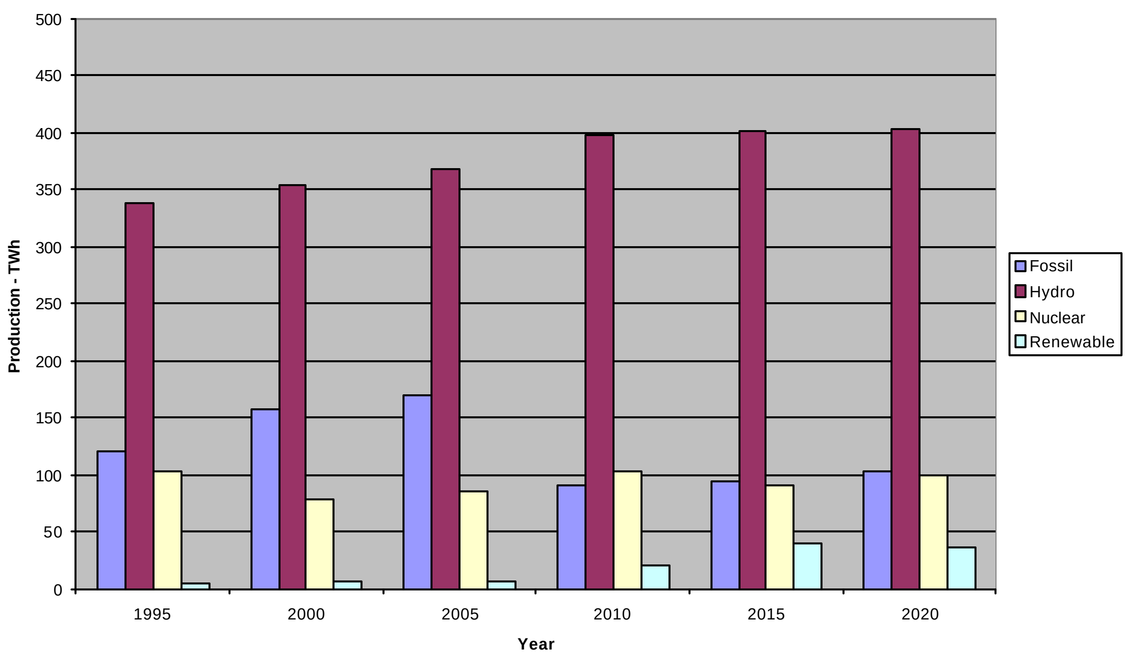


Figure 13 - Canada's Emissions from Electricity in 2010

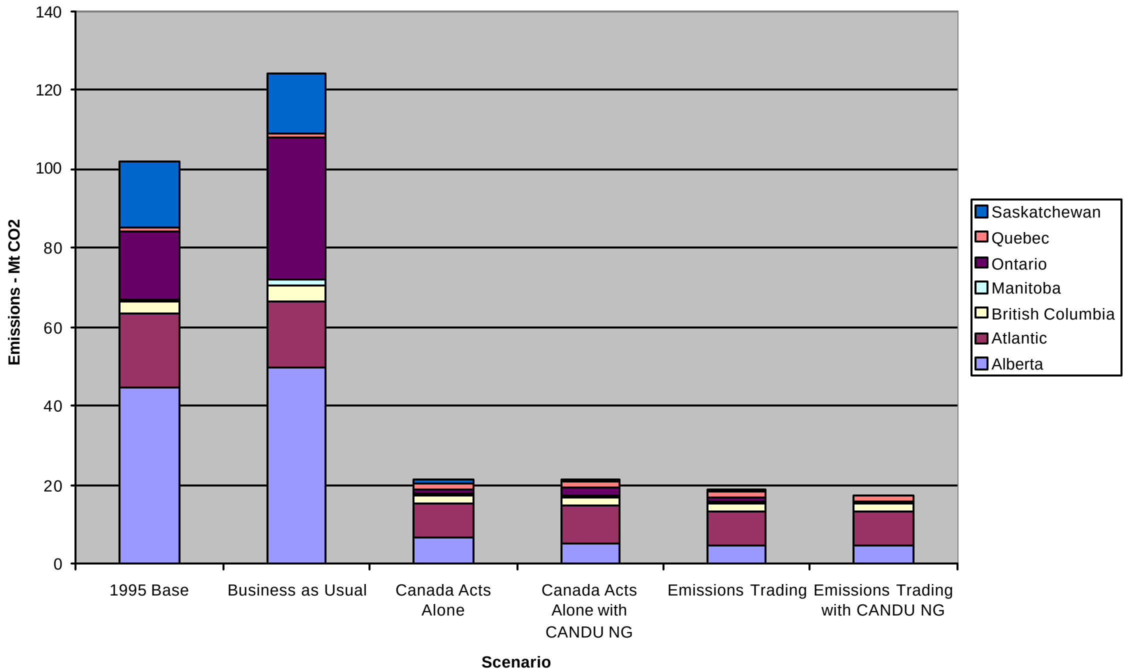


Figure 14 - Canada's Emissions from Electricity in 2020

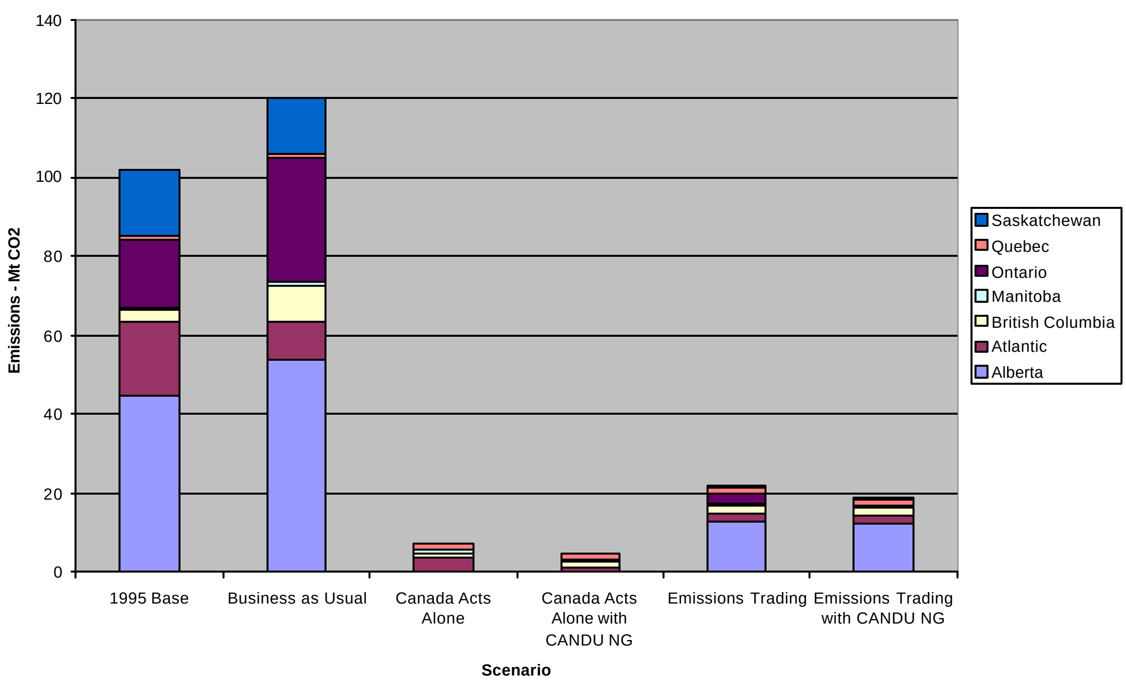


Figure 15 - Decisions to Install Additional CANDU 6 Capacity
Canada Acts Alone (Case 1)

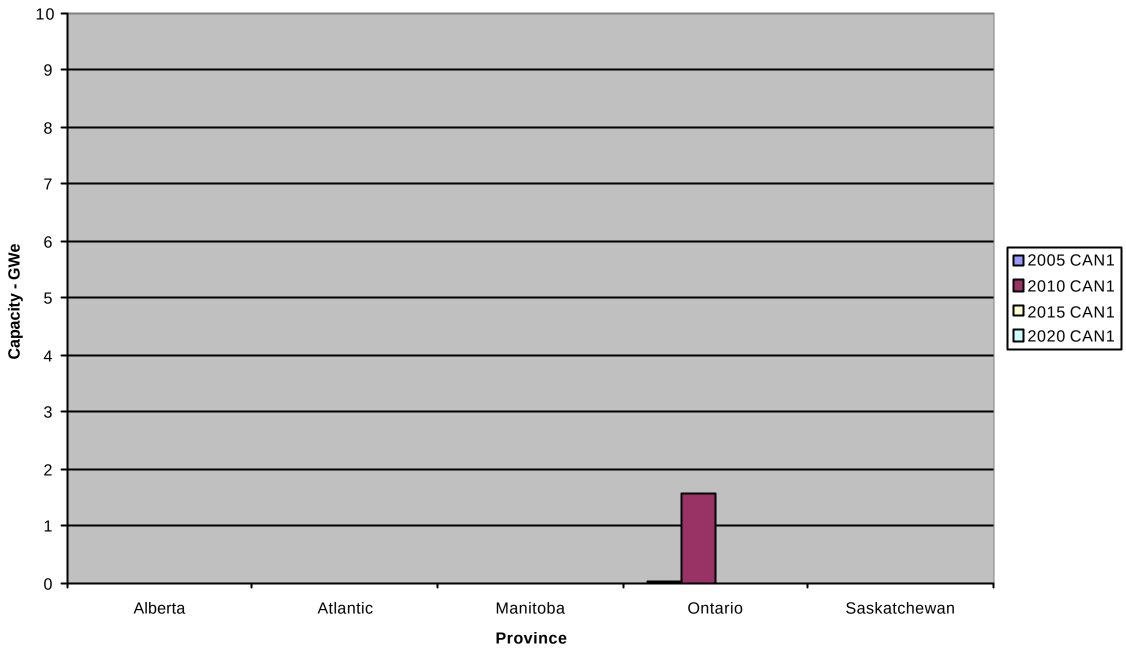


Figure 16 - Decisions to Install Additional CANDU NG Capacity
Canada Acts Alone (Case 2)

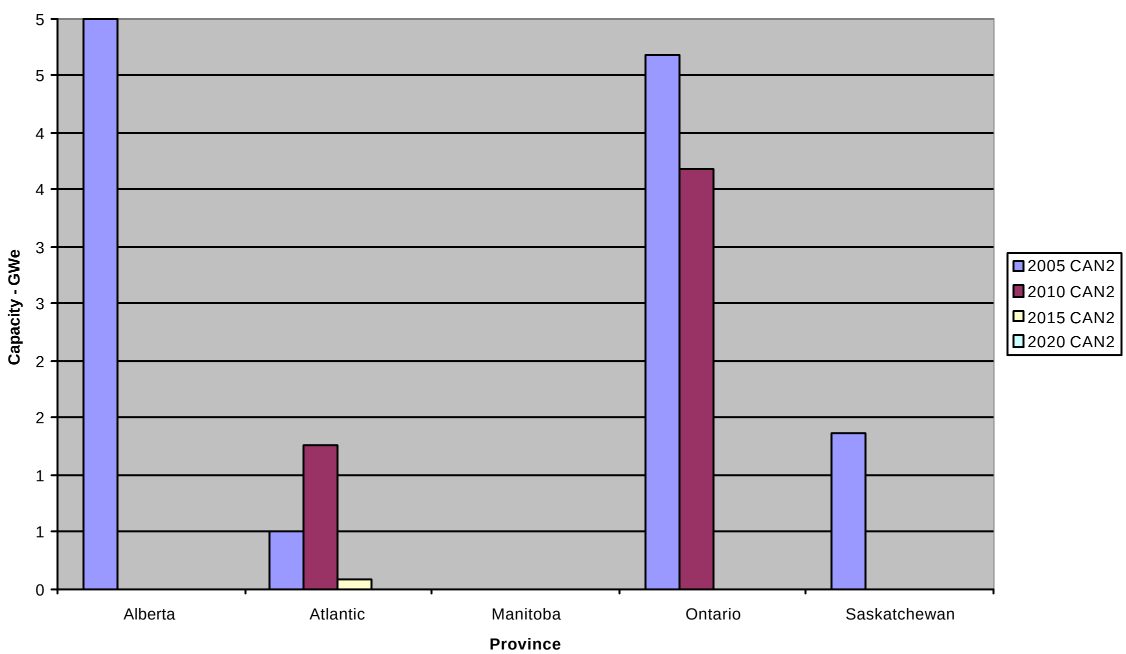


Figure 17 - Decisions to Install Additional CANDU NG Capacity International Emissions Trading (Case 4)

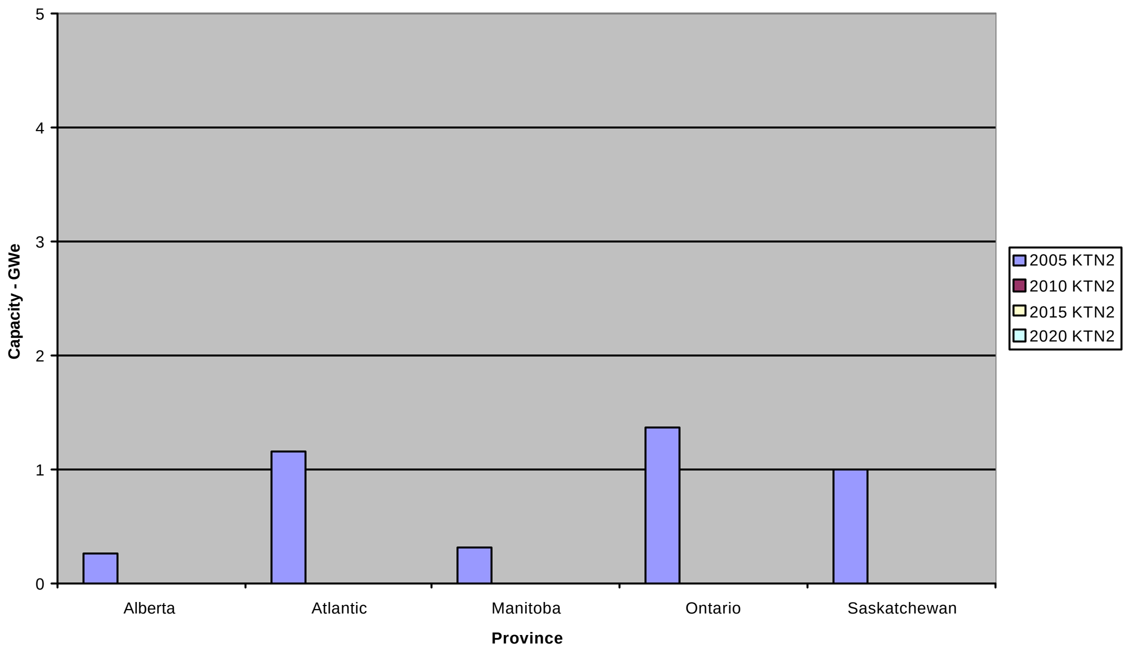
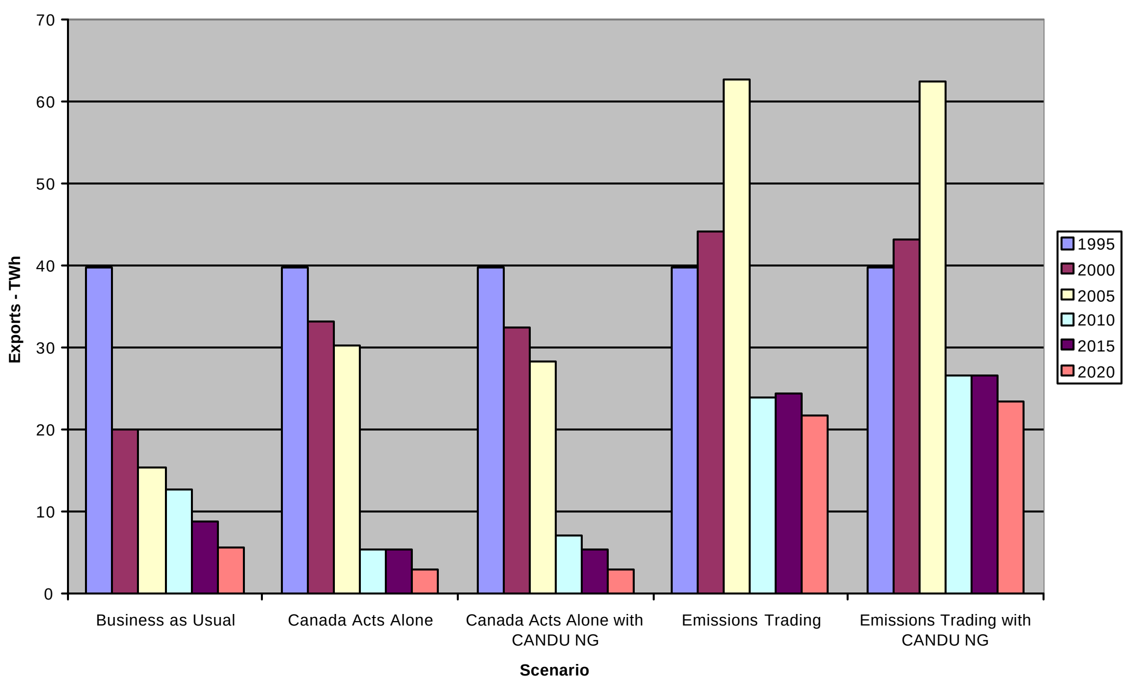


Figure 18 - Canada's Exports of Electricity



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