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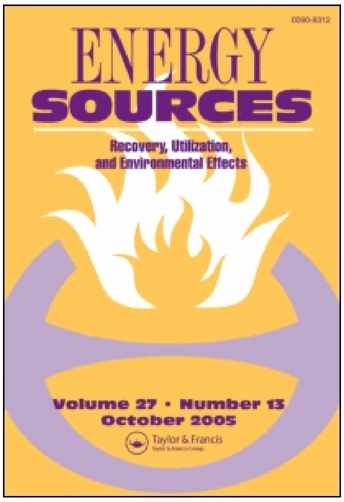

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CCEM: A City-cluster Energy Systems Planning Model

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Abstract *An understanding of complex interactions among energy, environmental, and economic activities is important for making decisions to support sustainable economic development and environmental protection. Energy models at global, national, and provincial levels are effective tools used for examining these interactions. However, these models are inadequate for a city-cluster jurisdiction such as the Toronto-Niagara Region (TNR), Canada, which has unique economic and energy characteristics. The objective of this study is to develop a City-cluster Energy Systems Planning Model (CCEM) and apply it to the TNR as a case study. It is demonstrated that the model can be effectively used for supporting energy planning, environmental management, and greenhouse gas (GHG) reduction in a city-cluster jurisdiction.*

Keywords energy planning, energy system, environment management, greenhouse gas, Kyoto protocol, optimization, renewable energy

1. Introduction

Energy plays important roles in a variety of human activities, including its production, processing, and consumption (Sailor, 1997; Liv et al., 2000). These activities will not only interact with each other but also affect the environment. Understanding these interactions will help provide decision support for managing a number of related human activities (Huang and Chang, 2003). Energy models are effective tools specifically developed for simulating such an energy-management system under a range of environmental, economic, and policy scenarios (Goldstein, 1995; Liv et al., 2008).

A number of energy models were developed to describe energy supply and demand and the related technologies in terms of energy efficiency and cost in a global, national, or provincial jurisdiction. The Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) (Schrattenholzer, 1981), and MARKAL (Fishbone et al., 1983) were accredited as the first generation energy systems models.

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The Australian Bureau of Agricultural and Resource Economics (ABARE) developed an energy system model for Australia to assess the impacts of Australian energy policy and the mandated target for renewable electricity (Naughten, 2002). Stocks and Musgrove (1984) developed a regional energy system model for Western Europe. Kambo et al. (1991) developed an urban energy model for the city of Delhi in India. Haurie (2001) presented a Markal-Lite model for an urban energy system in Geneva with a focus on industrial energy activities. Richter and Hamacher (2002) built an integrate model for energy and environment management with a case study for Augsburg, Germany.

Lin et al. (2004) proposed a regional energy systems planning model for the Province of Saskatchewan, Canada. Lin and Huang (2008) and Lin et al. (2008) developed two regional energy systems planning models with North America context. Cai et al. (2008) developed a regional energy systems planning model for the Region of Waterloo, Canada.

However, the existing global, national, and provincial models are too aggregated to provide specific insight into detailed characteristics and interactions within a city-cluster energy system. They are incapable of addressing the unique environmental and socioeconomic features of an urban system. Moreover, they can hardly reflect the sensitivity of energy activities to climate change due to the geographically distinct impacts of climate change and different residential and commercial energy consumption behaviors (Ruth and Amato, 2003). In addition, the existing urban models are unable to handle the complex relationships among adjacent cities in a region.

Therefore, the objective of this study is to develop a City-cluster Energy Systems Planning Model (CCEM) and apply it to the Toronto-Niagara Region (TNR), a typical city-cluster region located in central Ontario, Canada. The model will be built through probing the unique features of energy processing, transmission, and consumption in the TNR. The developed model will then support (a) decision of energy supply and demand in a business-as-usual case, (b) evaluation of the impacts of greenhouse gas (GHG) reduction on energy sectors, (c) identification of the least-cost mitigation strategies for meeting the Kyoto target, (d) examination of the effects from the phase-out of coal-fired power generation in the region, and (e) exploration of the potential impacts of the investment for renewable power technologies in the clustered cities.

2. Complexities of City-cluster Energy Systems

Typically, a city-cluster region combines a number of economically important cities in a closed geographic area that may also include rural and other land uses. In a national and provincial energy system, the relations within an energy system can be summarized into three types. First, competitive relations exist among energy resources or technologies; for example, various technologies will compete to provide electricity based on different economic and environmental features. Second, cooperative relations exist among energy activities; for example, mixed utilization of energy or technologies is usually considered in production, processing, and consumption. Third, the interactive relations are among supplies, demands, and technologies associated with energy production, processing, distribution, and consumption; for example, cheaper energy will increase demands, which in turn will affect energy production, processing, and distribution.

The degree to which these relations are mirrored within a city cluster depends on the structure of an energy grid, i.e., the scale at which distribution decisions are made. There are other unique economic and environmental features of concerns: (a) cities tend to be the loci of economic activities and population growth; the impacts of economic development and population growth affect all energy activities in the city by affecting energy production and consumption; (b) although, in a city-cluster system, the energy exploration and resources may be limited, the cluster often contains significant energy processing or transformation activities such as refining and electricity generation and large consumers across all sectors; (c) unique local environmental issues are factors that affect energy consumption such as the urban heat island; emissions of GHG and other pollutants that are associated with energy activities tend to be more concentrated, and public concern for air quality will affect the energy activities in the system; (d) cities are more vulnerable to the impacts of climate change due to the high concentration of people and infrastructure (SRC, 2001); such impacts cannot be effectively reflected in a provincial or national system due to geographically distinct impacts of climate change (Ruth and Amato, 2003).

The city-cluster energy system also shows different characteristics in comparison with an urban energy system due to the strong interactions among various energy-related activities in multiple cities. For example, policy to reduce energy prices will affect the energy supplies and demands; pollutants generated in one city will affect the ambient air quality of the others. In addition, a diversity of energy options is available in a city-cluster system that might not exist in any single city. Moreover, energy-related activities in one city may rely on or compete with those in the other cities.

3. Overview of the TNR's Energy System

The TNR is a typical city-cluster region located on the northwest shore of Lake Ontario, Canada. The region includes distinct airsheds and watersheds bounded by the Oak Ridges Moraine, the Niagara Escarpment, and Lake Ontario. Population, industry, and other economic activities are highly concentrated in this region (Chiotti, 2001). Seven upper-tier cities or regional governments—Toronto, Halton, Peel, Druham, York, Hamilton-Wentworth, and Niagara—cover less than one eleventh of the entire Province of Ontario, but account for 47% of the province's total population. The population in the Greater Toronto Area (GTA) alone is projected to grow from 5.1 million in 1999 to 7.5 million by 2028 (Ontario Ministry of Finance, 2000; Urquizo et al., 2003). In the TNR, the amount of primary energy consumption is more than a half of that in the entire Province of Ontario. The consumption by industrial, transportational, commercial, and residential sectors is large, while that by agriculture and forestry is small enough to be neglected in the analysis. The amount of renewable resources in the region is potentially high. However, as the energy sector is weighted heavily toward non-renewables (coal, oil, and natural gas), the TNR relies on imports of them from western Canada or the international market because the region's energy resources are very limited. Most of the coal in the TNR is used for electricity generation, which is responsible for a large part of GHG and air-pollutant emissions. The region contains a large amount of energy processing and transforming facilities (e.g., oil refining and electricity generation).

In Ontario, the majority of electricity is fed into one grid and then distributed throughout the province. It is extremely difficult to associate the generation at one facility with a particular city or region in the province. In order to proceed with the analysis based on the CCEM, it is assumed that all of the facilities within the region (and those that cause air pollution problems) would supply electricity to the TNR. It is thus interesting to know how much additional electricity must be imported from the provincial grid or other external sources. Currently, coal, nuclear, and hydro energy are widely used for generating electric power in the TNR. Hydro power is a major source of electricity, but, unfortunately, additional generation is only available at higher cost and limited by source availability. Nuclear power, another main source for electricity, is reluctant to be increased because of the safety concerns by the public. A small amount of wind power has been available since 2002. Additional power is available at considerably higher cost than the electricity from conventional fossil fuel sources. Solar, wind, and additional hydro may be favored as new energy sources in order to mitigate GHG emissions and air pollution.

Demands can be categorized into five sectors according to end-user types: agricultural, residential, commercial, industrial, and transportational. However, their contributions to energy consumption are significantly different from each other. As noted above, consumption by agriculture and forestry can be neglected, while industrial consumption is the highest due to massive manufacturing and energy processing activities in the region. Consumption by the commercial sector is lower than that by the industrial but higher than that by the residential. Energy consumed by transportation is also high due to a large number of personal and commercial vehicles and the lack of public transit alternatives outside of the City of Toronto.

4. Development of a CCEM for the TNR Energy System

Mathematically, the objective of the CCEM is to minimize total system cost subject to a series of constraints, which represent a variety of economic, technological, and environmental limitations. The objective function is a linear formulation of different sources of energy supply options and technologies that moves energy carriers from energy supply side to demand side. It includes (a) resource supply, (b) stockpiling, (c) process activity, (d) investment and capacity, (e) electricity generation, (f) electricity from heat and electricity co-generation, and (g) heat generation. Temporally, the developed CCEM for the TNR covers a time horizon of 45 years (1988–2032), which is divided into 9 periods with each covering 5 years. To reflect the impact of the Kyoto targets, the model begins from the 1988–1992 period. Spatially, the entire region, including Toronto, Halton, Peel, Durham, York, Hamilton-Wentworth, and Niagara, is considered as a system. Technologically, the model reflects interactions among various system components that have environmental and economic implications.

Energy supply options are classified into fossil and renewable resources. Each option has its own sub-sectors representing specific resources. Fossil resources include mining activities of coal, crude oil, and natural gas. Renewable resources include biomass, wood, hydro, solar, geothermal, and wind power. When the amount of production for mined and renewable resources cannot meet demands, imports become necessary. When the production is greater than domestic demands and export price is attractive or the production cost is relatively low, exporting energy becomes possible.

The model is driven by a set of energy demand sectors, based on a variety of demographic, economic, technological, sociological, and environmental factors—residential, commercial, industrial, and transportational. Each sector has many separate segments, which can be further categorized into a number of sub-sectors, representing one type of energy consumer. The model is configured to reflect changes in end-user demands resulting from variations in the cost and thus the price of supplying these demands. These changes may be brought about directly through emission price changes or indirectly through reconfiguration of demand technologies.

The report entitled Canada's Emissions Outlook—An Update (CEOU) (AMG, 1999) was used for demand projections in commercial, residential, and transportational sectors. For industry, the CEOU was not directly usable. During the calibration task, minor revisions were needed for some projections in order to match the actual energy consumption as per the CEOU forecast. In terms of demand, climate change would have significant impacts on patterns and amounts of energy consumption; milder winter temperature would reduce the energy needed for space heating, while higher summer temperature would increase the demand for electricity. The impacts on peak demands due to extreme weather were ignored since each planning period has a 5-year span.

In the model, various technologies are applied to deal with supply and demand options. On the supply side, only a small amount of energy resources can be used directly. Most of the resources need to be converted, transformed, or processed before they can be utilized by consumers or other technologies. In the model, three kinds of technologies are considered. Electricity conversion technologies are used to convert the energy resources to electricity, which can be transmitted and distributed to end users. Process technologies are used to transform the energy resources to various energy carriers such as gasoline, diesel, and alcohol. With demand technologies, all energy carriers, including electricity, can be used by end users. Since different technologies have varied energy consumption efficiencies, emission coefficients, capital investments, and operating costs, they would compete with each other in the model to supply a mixture of various options to end users.

GHG emissions are modeled by two parts. One is considered in each technology such as electricity conversion, oil refinery, natural gas processing, and resource mining. The amount of emission is determined by each technology according to its emission efficiency. The other part is associated with the fuel consumed by end users. The emission in this part is calculated with a fixed ratio to the amount of fuel consumed. In addition to demand projections, the model was calibrated to match GHG emissions reported by CEOU and Environment Canada. Calibration to GHG emissions was often an almost automatic consequence of fuel-consumption calibration, since the majority of GHG emission is purely a function of fuel combustion. CO_2 sequestration technologies are incorporated within the model as an option for reducing GHG emissions. The enhanced oil recovery and forestation sequestration technologies are considered, although their contributions are insignificant in practice.

To better reflect the interaction between energy supply and demand, annual electricity supply, residential demand, and commercial demand are partitioned into six time-segments, including winter day, winter night, summer day, summer night, fall-spring day, and fall-spring night. This accommodates electricity production variations throughout a year. For example, the production of hydro power could be decreased in the winter and increased in the summer. The consumption of energy by end users is also allocated into particular time segments. For instance, most of electricity for space cooling would be consumed in the summer, and vice versa for space heating. Additional demand for electricity in the summer leads to investment in additional power generation capacity even if the redundant capacity cannot be utilized in the winter. Additional demand for space heating is met by expanding the capability of infrastructure, transportation, and storage of natural gas or fuel in the winter.

5. Energy and Environment of Systems Planning under Business-as-usual Condition

The business-as-usual (BAU) case is designed to plan the TNR energy system without any exterior constraints. With the maximum possible endogenous energy carriers, technologies, and resources, the model minimizes the total cost of the TNR's energy system in terms of the sum of the discounted cost over a 4-year horizon (the discount rate is assumed to be 7% per year). Subject to all endogenous constraints, the energy supply will be configured to meet the demand. The detailed costs are provided in Table 1.

As shown in Table 1, the total minimum system cost of TNR's energy supply and demand would be $101,064 million ($1990) over the 45-year horizon. Resource production cost would account for a small part of the total cost, because there are small reserves and productions of coal, crude oil, and natural gas in the region. The costs of fuel delivery as well as the fixed and variable costs for operation and maintenance (related to supply and demand technologies) would be $37,621 million, accounting for 37.2% of the total expenditure. The cost of investment in technology would be low. This suggests that the existing energy supply technologies might meet the region's energy demand, and the model opts to increase imports or to decrease exports of energy rather than to invest in new technologies. The net import cost would be responsible for the largest proportion of the total cost (60.3%), since a large amount of energy imports is needed to meet demand. The cost of CO_2 sequestration technologies would be zero because they do not appear when GHG emission reduction is not required.

The total production of electricity would increase steadily from 261.64 PJ per year in the first 5-year period (period 1) up to 385.78 PJ per year in period 9 (Table 2). Currently, only coal-fired, natural gas-fired, hydro, and nuclear technologies are widely installed to meet domestic electricity demand in the TNR. Among these options, nuclear power would account for the largest proportion of electricity generated in the region over the 45-year horizon, increasing from 40.7% in period 1 to 42.6% in period 9. In period 2, its production would increase abruptly from 102.12 PJ in period 1 to 172.78 PJ, then decrease to 161.45 PJ in period 3 and stabilize in the following years due to the retirement of one unit in the Pickering A Plant.

Coal-fired electricity generation would rank second, generating 34.0% of the total electricity in period 1 and increasing to 39.9% by period 9 due to its relatively lower cost. Its production would drop sharply from 85.41 PJ in period 1 to 59.71 PJ in period 2 due to the initiation of more nuclear facilities. From period 3, its contribution would increase steadily, reaching 154.01 PJ in the final period. Electricity generated from natural gas would be an insignificant option in the electricity grid due to its relative high cost. Renewable energy, including hydro, biomass, and wind would be responsible for generating the remaining electric power. Hydro power is the third largest source for

Table 1

Discounted cost for meeting energy demand in periods 1 to 9 (million $1990)

Item	BAU	Coal phased-out (scenario 1)	Renewable power (scenario 2)	Kyoto target (scenario 3)
Total resource production	345.04	345.04	345.04	345.04
Total investment in technology	809.92	2,852.67	3,101.48	3,074
Investment of salvage cost	−164.85	−407.6	−381.38	−658.7
Net import cost	65,553.89	65,837.69	65,117.64	70,150.85
Other total expenditure	36,835.36	36,896.44	36,785.64	36,045.58
Total discounted cost	103,379	105,525	104,968.44	108,957.8

Note: BAU: business-as-usual case; scenario 1: coal phased out; scenario 2: 10% power is generated from renewable source; scenario 3: Kyoto target.

Table 2
Electricity production by fuel type in BAU and scenarios 1 to 3 (PJ)

Period	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total (BAU)	250.98	284.31	292.84	308.02	327.14	342.23	355.63	370.76	385.78
Total (scenario 1)	250.98	284.31	292.84	308.02	326.99	342.07	355.48	370.61	385.75
Total (scenario 2)	250.98	284.31	292.84	308.02	325.78	340.87	355.29	369.40	384.55
Total (scenario 3)	250.98	284.31	292.84	308.02	298.57	311.02	287.77	291.56	308.60
Coal-fired (BAU)	85.41	59.71	79.39	91.18	110.34	123.14	137.09	151.19	154.01
Coal-fired (scenario 1)	85.41	59.71	79.39	91.18	0.00	0.00	0.00	0.00	0.00
Coal-fired (scenario 2)	85.41	59.71	79.39	90.50	80.88	89.22	96.66	97.88	97.88
Coal-fired (scenario 3)	85.41	59.71	79.39	91.18	10.20	0.00	0.00	0.00	0.00
Gas-fired (BAU)	2.01	0.00	0.05	2.37	2.35	2.54	1.5	1.56	8.46
Gas-fired (scenario 1)	2.01	0.00	0.05	3.05	74.88	82.15	88.20	103.26	107.38
Gas-fired (scenario 2)	2.01	0.00	0.05	2.37	0.18	1.08	3.17	9.18	10.66
Gas-fired (scenario 3)	2.01	0.00	0.05	3.05	33.63	33.38	7.29	0.00	0.00
Biomass (BAU)	0.00	0.00	0.21	0.52	0.52	0.52	0.31	0.56	0.81
Biomass (scenario 1)	0.00	0.00	0.07	0.38	0.58	0.58	2.52	2.66	2.66
Biomass (scenario 2)	0.00	0.00	0.07	1.06	2.02	2.51	2.41	6.16	6.16
Biomass (scenario 3)	0.00	0.00	0.07	0.38	2.52	2.52	5.69	6.12	6.13
Hydro (BAU)	61.37	51.83	51.83	52.53	52.53	54.65	55.41	55.41	55.41
Hydro (scenario 1)	61.37	51.83	51.83	52.53	52.53	54.65	55.41	55.41	55.41
Hydro (scenario 2)	61.37	51.83	51.83	52.53	52.53	54.65	55.41	55.41	55.41
Hydro (scenario 3)	61.37	51.83	51.83	52.53	52.53	54.65	55.41	55.41	64.52
Wind (BAU)	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.81	3.00
Wind (scenario 1)	0.00	0.00	0.05	0.05	9.62	9.62	14.35	14.35	14.35
Wind (scenario 2)	0.00	0.00	0.05	0.05	10.62	11.91	13.21	15.40	16.56
Wind (scenario 3)	0.00	0.00	0.05	0.05	4.15	14.35	14.35	14.35	16.56
Nuclear (BAU)	102.12	172.78	161.45	161.43	161.41	161.39	161.37	161.35	164.36
Nuclear (scenario 1)	102.12	172.78	161.45	161.43	189.37	194.54	194.46	194.38	194.30
Nuclear (scenario 2)	102.12	172.78	161.45	161.43	161.41	161.39	161.37	161.35	171.92
Nuclear (scenario 3)	102.12	172.78	161.45	161.43	194.62	194.54	194.46	194.38	194.30
Solar (BAU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solar (scenario 1)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.11
Solar (scenario 2)	0.00	0.00	0.00	0.00	19.56	21.50	23.46	25.42	27.38
Solar (scenario 3)	0.00	0.00	0.00	0.00	0.00	11.04	11.04	20.76	44.97

power generation. In period 1, it would reach a peak production of 61.37 PJ, then decrease to 51.83 PJ in period 2, and remain relatively stable in later periods. The contribution of wind to total electricity generation would be insignificant, but, by period 9, its production would be as high as 3.00 PJ, being 6 times greater than that in period 5.

GHG emissions can be generated in any sectors when no constraints are put on. The resulting GHG emissions, by sources, are presented in Table 3 and Figure 1. In the BAU case, energy development and utilization would result in 92.44 million tonnes of CO_2-equivalent emission in period 1 (1988–1992). Electricity generation would account for 29.2% or 26.99 million tonnes. Refineries would contribute 6.8% or 6.30 million tonnes. The remainder would be attributed to end-user demands. Residential consumption would be responsible for 9.9% or 9.13 million tonnes of the emissions and commercial consumption would represent 5.5% or 5.04 million tonnes. Industrial consumption would generate 24.1% of the total emission or 22.25 million tonnes, while transportation would account for 24.6% or 22.71 million tonnes, almost equaling the amount associated with industrial consumption. The emissions from crude and gas production are not examined

Table 3
GHG emissions by source in BAU and scenarios 1 to 3 (million tonnes)

Time period	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total (BAU)	92.44	87.04	96.46	104.3	113.82	121.94	129.8	136.84	141.78
Total (scenario 1)	92.44	87.04	96.46	104.18	87.98	93.22	97.91	102.48	106.36
Total (scenario 2)	92.44	87.04	96.46	104.11	104.69	111.80	118.33	122.41	125.91
Total (scenario 3)	92.44	87.04	96.46	104.30	86.90	86.90	86.90	86.90	86.90
Electricity (BAU)	26.99	18.67	24.79	28.78	34.4	38.14	42.01	46.06	47.66
Electricity (scenario 1)	26.99	18.67	24.79	28.66	8.56	9.43	10.15	11.69	12.24
Electricity (scenario 2)	26.99	18.67	24.79	28.59	25.27	28.00	30.57	31.63	31.79
Electricity (scenario 3)	26.99	18.67	24.79	28.78	8.41	4.21	1.09	0.26	0.18

Note: BAU: business-as-usual case; scenario 1: coal phased out; scenario 2: 10% power is generated from renewable source; scenario 3: Kyoto target.

further in this study because their amounts would be much less than those from the other sectors.

Over all periods (1988–2032), the total simulated GHG emissions would grow steadily from 92.44 million tonnes in period 1 to 136.84 million tonnes in period 9, with the only exception occurring in period 2 when the new nuclear plant was brought on line. A large amount of electricity generated from the nuclear plant will not only meet the increasing demands but also compete with coal-fired plants, resulting in a significant reduction of GHG emissions. Most of the GHG emissions from the electricity generation sector would be attributed to coal-fired plants. Currently, there is a capacity of 1,140 MW at the Lakeview Plant in Mississauga and a capacity of 3,920 MW at the Nanticoke Plant

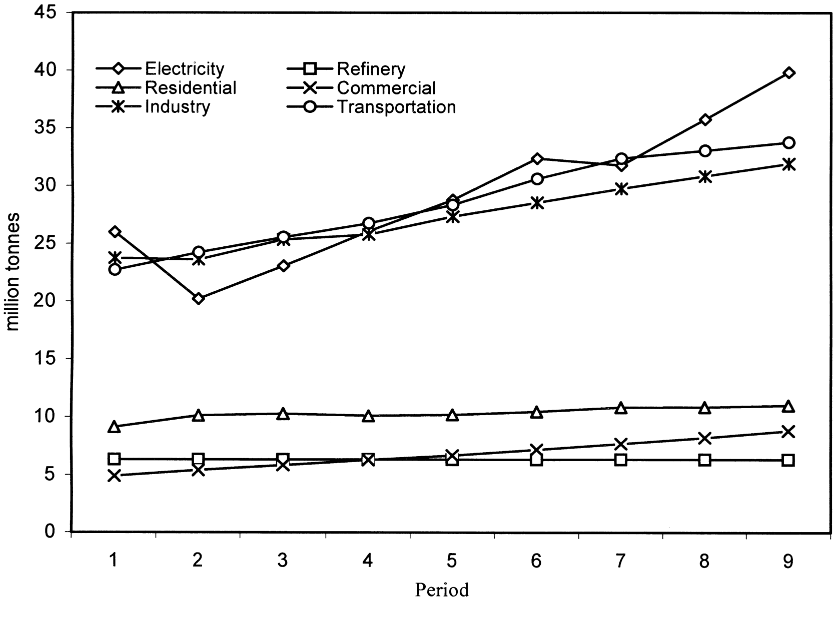

Figure 1. GHG emissions by source under BAU condition.

Table 4
NOx emission by source in periods 1 to 9 (ktonnes)

Period	1990	1995	2000	2005	2010	2015	2020	2025	2030	Total
Total	145.55	133.78	150.95	163.50	177.24	189.17	199.51	206.95	211.78	7,892.16
Industry	13.25	13.39	14.19	15.55	16.53	17.28	18.05	19.05	20.11	737.08
Commercial	2.33	2.54	2.63	2.79	2.95	3.14	3.36	3.57	3.79	135.40
Residential	4.27	4.66	4.63	4.53	4.56	4.64	4.81	4.81	4.81	208.55
Transportation	64.97	69.14	72.86	76.38	81.27	87.76	92.79	94.66	96.57	3,682.03
Refinery	5.41	5.41	5.41	5.41	5.41	5.41	5.41	5.41	5.41	243.27
Electricity	55.18	38.50	51.09	58.76	66.51	70.95	75.10	79.45	81.10	2,883.30

in the Lake Erie Region. Nanticoke is included in the study as it is required to meet peak summer demands, and its emission outputs contribute to air pollution problems in the TNR.

Under the BAU condition, the total NO_x emission associated with energy-related activities would be 145.55 ktonnes in period 1 (Table 4). Electricity generation would account for 38% or 55.18 ktonnes due to the utilization of internal combustion and coal-fired technologies. Refineries would contribute 3.7% or 5.41 ktonnes. Residential energy consumption would account for 2.9% or 4.27 ktonnes, while that from commercial consumption is only 2.33 ktonnes, being the lowest in the end-user demand sector. Industrial consumption would represent 9.1%, and transportation would account for 44.6%, being the largest source of NO_x emission. Over all periods, the total simulated NO_x emission would increase from 145.55 ktonnes in period 1 to 211.78 ktonnes in period 9, with the only exception occurring in period 2 due to the reduced utilization of coal-fired capacity and the internal combustion power plant. The NO_x emission associated with electricity generation would increase 47% (from 55.18 ktonnes in period 1 to 81.10 ktonnes in period 9), along with the continuous increase of coal-fired electricity production. Similar to the GHG emissions, NO_x emissions from the refining sector would remain steady, and that from the end-user sector would increase in response to the increasing energy demand. By period 9, NO_x emissions from electricity, refining, residential, commercial, industrial, and transportational would account for 38.3, 2.6, 2.3, 1.8, 9.4, and 45.6% of the total emission, respectively.

6. Energy and Environmental Policy Scenarios

6.1. Scenario 1: Phasing Out of Coal-fired Power

For the TNR, it is assumed that coal-fired power generation would be phased out by the period of 2008–2012 (period 5). The modeling result shows that the total discounted cost would increase from \$103,379 million in BAU to \$105,525 million (\$1990) under this scenario. Resource production would remain unchanged, while the investment in technology would be increased by \$2,042.75 million to build additional electric power capacity. The net import cost would be increased by \$283.8 million, primarily due to the increased domestic demand of natural gas for generating electricity. The other expenditures would increase by \$61 million, while the salvage cost would decline by \$242.75 million (Table 1).

The TNR electricity grid is assumed to be independent. The model will opt to use other technologies to replace the coal-fired one, or to import electricity from the other regions. Based on the existing employment, tax, and GDP, the import cost would be high. Thus, the model would turn into natural gas, biomass, wind, and solar power due to their economic efficiencies. By period 5, natural gas technology would be the largest source for power generation, increasing from 2.35 PJ in the BAU case to 74.88 PJ under this scenario. Nuclear power would be another major option to be selected. The additional power would be provided by rebuilding the retired unit in Pickering A. This rebuilt capacity would generate about 28 PJ in period 5. Investment in renewable energy would become economically feasible when the nuclear and natural gas options cannot meet the increasing electricity demand. By period 5, the utilization of wind would increase from 0.05 PJ in the BAU case to 9.62 PJ under this scenario. By period 7, wind power production would reach 14.35 PJ and remain stable until period 9. More biomass would also be used by period 7, with increments of 2.52 PJ in period 7 and 2.66 PJ in period 9. Investment in solar power would only occur in period 9 due to its high capital cost. However, its production would be much higher than that of biomass in that period. This indicates that, once the investment cost of solar power decreases to a certain level, its utilization will become significant due to the unlimited resources of it (Table 2).

GHG emissions associated with electricity generation would be significantly affected in response to the retirement of the coal-fired plant. The emissions from electricity generation under this scenario would drop by 75.1% or 25.84 million tonnes and 74.3% or 35.42 million tonnes less than that in the BAU case in periods 5 and 9, respectively (Table 3). The remaining emissions, ranging from 8.56 million tonnes in period 5 to 12.24 million tonnes in period 9, would be from natural gas-fired and biomass power generation in order to meet the demand caused by the phasing out of coal-fired power generation. The reduced emission from electricity would thus lower down the total emission in the TNR by 22.7% in period 5 and 33.3% in period 9.

6.2. Scenario 2: Renewable Energy for Power Generation

The Clean Air Renewable Energy Coalition (CARE) recently released its vision for a low-impact renewable energy future for Canada, involving solar thermal and solar photovoltaic (PV) technologies, wind power, geothermal energy, micro and mini hydro technologies, and biomass and other renewables as described in the Eco Logo definition from Environmental Canada. The potential for renewable energy in Canada is enormous. The CARE goal is to have low-impact renewable energy account for at least 7% of Canada's electricity production by 2010 and 15% by 2020. This study will take an aggressive scenario by assuming 10% of electricity production from renewable power generation technologies in period 5. The technologies included in the renewable category would compete with each other based on a least-cost strategy and the constraint of resource availability. In response to this assumption, the investment in technology would increase by $2,291.56 million ($1990) compared to that in the BAU case. The net import cost would decrease by $436.05 million ($1990) due to the reduced gas and coal demands for electricity generation. The other expenditure would be reduced by $49.72 million compared to that in the BAU. Such reductions could be attributed to the decreased operational and distributional costs in relation to electricity generation from renewable energy. The capital investment in renewable technology would be much higher than that in fossil fuel technology. This would not only reduce the price of electricity but also increase the diversity and security of energy supply (Table 1).

The biomass, including solid wastes, wood wastes, and landfill gas would provide 2.02 PJ of energy starting from period 5 (almost tripling the contribution in the BAU case) and 6.16 PJ in period 9 (6.6 times greater than that in the BAU case). The utilization of wind power would continue to increase and reach 16.56 PJ in period 9, being 5 times more than that of the BAU case. Although the capital investment of solar power technology is much higher than that of wind and biomass, the abundant solar energy would lead the model into solar thermal and solar PV when wind and biomass reach their maximum availability. The solar power production would be 19.56 PJ by period 5, and continue to increase to 27.38 PJ in period 9, surpassing wind power during periods 5 to 9.

The coal-fired electricity generation would also be increased during these periods, from 80.88 PJ in period 5 to 97.28 PJ in period 9. However, its contribution would be much lower than that in the BAU case, decreasing by 26.7% or 29.46 PJ in period 5 and by 36.4% or 56.13 PJ in period 9. The gas-fired generation would increase significantly from 0.18 PJ in period 5 to 10.66 PJ in period 9, being more or less than that in the BAU case. Nuclear and hydro power would remain unchanged in reference to the BAU case, due to their relatively high cost and the limitations of resource availability (Table 2).

GHG emissions from electricity generation under this scenario would be 26.5 and 33.3% less than that in the BAU case by periods 5 and 9, respectively. However, they would be 195 and 160% higher than those under scenario 1 by periods 5 and 9, respectively, as coal-fired facilities are still used due to their cost advantage. The total emission levels would be correlated to those from electricity generation. By periods 5 and 9, the emission would be 14.1 and 11.2% lower than those under the BAU case and 19.0 and 18.4% higher than those under scenario 1 (Table 3).

6.3. Scenario 3: Reflection of Kyoto Protocol Impacts

The Kyoto Protocol was established under the United Nations Framework Convention on Climate Change (UNFCCC) to set initial targets for reducing GHG emissions (UNFCCC, 1997). Under the Kyoto Protocol, Canada has committed to reduce GHG emissions to 94% of the 1990 level. Under the BAU case, the annual GHG emissions in the TNR would reach 113.82 million tonnes by period 5 and 141.78 million tonnes by period 9. The target can be achieved in multiple ways, each with varied actions, costs, and consequences. For each option, the model has to satisfy both the least cost objective and the Kyoto emission cap.

The GHG emissions under the Kyoto target would be reduced by 19% from 113.82 million tonnes under the BAU to 86.90 million tonnes under this scenario by period 5, and would become stable in the remaining periods (Table 3). Most of the reduction would be borne by the electricity sector, decreasing from 34.40 million tonnes under the BAU to 8.41 million tonnes under this scenario in period 5. The decreasing utilization of coal-fired capacity would account for all of the reductions. This would then be replaced by gas-fired and renewable technologies with lower environmental emission coefficient. In the subsequent periods, the gas-fired technology would be replaced by renewable technologies with even lower emission coefficients. By period 9, the emission from electricity generation would be reduced to 0.18 million tonnes, with all of the fuel-fired technologies being phased out. In period 5, most of the reduction would be covered by nuclear power and natural gas-fired facilities, with increments of 33.15 and 31.28 PJ, respectively; wind and biomass power would also contribute 4.10 and 2.0 PJ, respectively.

However, due to the high costs of these technologies, the total electricity production would be 28.37 PJ less than that in the BAU case. Imports or other provincial power grids outside of the TNR would be utilized to fill the gap. In period 6, about 31.21 PJ of electricity would be imported in response to the increasing demand. By period 9, when both coal-fired and gas-fired power are phased out, electricity imports would reach 77.18 PJ; power from renewable energy would also increase significantly. The production of solar power would be more than double of that in the BAU case by period 8 due to the decreased capital cost and the unlimited solar energy. In period 9, wind power would also be increased in comparison with that under the BAU, and hydro power would be 9.11 PJ higher than that under the BAU due to the investment in micro and mini hydro (Table 2).

The total discounted cost over the 45-year horizon would be increased from $103,379 million ($1990) in the BAU case to $108,958 million when the Kyoto target is to be met. Most of the growth is attributed to the increased cost of electricity imports and the reduced revenue from fuel exports. As a result, the net fuel import cost would be increased to $70,150 million, being $4,596 million higher than that under the BAU. The investment of new power-generating capacities with low emission would cause an increase of $2,264 million in total investment for technology in comparison with that under the BAU. The other expenditures would be decreased by $790 million due to the lowered operating cost of the invested technologies (Table 1).

7. Conclusions

A City-cluster Energy Systems Planning Model (CCEM) was developed for regions composed of multiple cities. Environmental emissions were incorporated within the modeling framework to reflect the system's responses to varied policies. The developed CCEM was applied to the Toronto-Niagara Region for planning electricity generation, environmental emissions management, and policy response. The results indicate that the developed model was effective for optimizing energy production based on a least-cost strategy, assessing environmental emissions by source, and exploring economic and environmental consequences of different policies.

The developed model is also useful for supporting further studies in examining the impacts of variations in climatic and socio-economic conditions on the energy sectors. Moreover, the model could help provide an improved insight into the mechanism in terms of how human health, natural environment, urban infrastructure, and economic activities in a city-cluster region are affected by such variations.

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References

AMG. 1999. *Canada Emissions Outlook: An Update.* Ottawa, Canada.

Cai, Y. P., Huang, G. H., Yang, Z. F., Lin, Q. G., Bass, B., and Tan, Q. 2008. Development of an optimization model for energy systems planning in the Region of Waterloo. *International Journal of Energy Research* 32:988–1005.

Chiotti, Q. 2001. Climate Change, Energy, and Sustainability: Lessons from the Toronto-Niagara Region [cited February 12, 2004]. Available at http://www.cns-snc.ca/events/CCEO/graphics/3b_chiotti_paper.pdf

Fujii, Y., and Yamaji, K. 1998. Assessment of technological options in the global energy system for limiting the atmospheric CO_2 concentration. *Environ. Econom. Policy Stud.* 1:113–139.

Goldstein, G. A. 1995. Markal-Macro: A methodology for Informed Energy, Economy and Environmental Decision Making. New York: Brookhaven National Laboratory (BNL).

Haurie, A. 2001. MARKAL-LITE: *An Energy/Environment Model to Assess Urban Sustainable Development Policies* [cited 12 May 2004]. Available at http://ecolu-info.unige.ch /recherche/sutra/contributions/markal-lite_02.pdf

Huang, G. H., and Chang, N. B. 2003. The perspectives of environmental informatics and systems analysis. *J. Environ. Inform.* 1:1–7.

Kambo, N. S., Handa, B. R., and Bose, R. K. 1991. Linear goal programming model for urban energy-economy-environment interaction. *Energy Build.* 16:537–551.

Lin, Q. G., and Huang, G. H. 2008. IPEM: An interval-parameter energy systems planning model. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 30:1382–1399.

Lin, Q. G., Huang, G. H., and Bass, B. 2004. Power challenge for a cleaner energy future in Saskatchewan, Canada. *International Journal of Computer Applications in Technology* 22:151–159.

Lin, Q. G., Huang, G. H., Bass, B., and Qin, X. S. 2008. IFTEM: An internal-fuzzy two-stage stochastic optimization model for regional energy systems planning under uncertainty. *Energy Policy* (in press).

Liu, L., Huang, G. H., Fuller, G. A., Chakma, A., and Guo, H. C. 2000. A dynamic optimization approach for non-renewable energy resources management in a regional system under uncertainty. *Journal of Petroleum Science and Engineering* 26:301–310.

Liu, Z. F., Huang, G. H., and Li, N. 2008. A dynamic optimization approach for power generation planning under uncertainty. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 30:1413–1431.

Naughten. 2002. *Top-Down and Bottom-Up Models: Bridging the Gap'Canberra.* ETSAP seminar, Canberra, Australia.

Ontario Ministry of Finance. 2000. Ontario Population Projections, 1999-2028 [cited March 15, 2004]. Available at http://www.gov.on.ca/FIN/english/demog00e.pdf

Richter, S., and Hamacher, T. 2002. URBS—An Integral Model for Investigations on Future Urban Energy Systems [cited April 18, 2004]. Available at http://www.richter-info.de/files/Paper_PowerGen_2003_Richter.pdf

Ruth, M., and Amoto, D. A. 2003. Regional Energy Demand Responses to Climate Change: Methodology and Application to the Commonwealth of Massachusetts [cited January 12, 2004]. Available at http://www.puaf.umd.edu/faculty/papers/ruth/Energy-Climate_(M_Ruth).pdf

Sailor, D. J. 1997. Climate change feedback to the energy sector: developing integrated assessments. *World Resource Rev.* 9:301–316.

Saskatchewan Research Center (SRC). 2001. *Adaptability of Prairie Cities: The Role of Climate Current and Future Impacts and Adaptation Strategies, Saskatchewan, Canada*. [cited May 22, 2004]. Available at http://142.3.213.61/publications/chapter1.pdf

Schrattenholzer, L. 1981. The Energy Supply Model MESSAGE. IIASA Report RR-81-31, Laxenburg, Austria.

Stocks, K., and Musgrove, A. 1984. MENSA—a Regionalized Version of MARKAL, the IEA Linear Programming Model for Energy Systems Analysis. *Energy Sys Policy* 4:313–348.

Strubegger, M., McDonald, A., Gritsevskii, A., and Schrattenholzer, L. 1999. *CO_2DB Manual, Version 2.0.* Laxenburg, Austria: IIASA.

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

Urquizo, N., Auld, H., MacIver, D., and Klaassen, J. 2003. Toronto: The Climate Change Laboratory? Meteorological Service of Canada, Environment Canada, Canada [cited May 12, 2004]. Available at http://www.msc-mc.ec.gc.ca/saib/atmosphere/ccl/torCCL_e.cfm

Van der Voort, E. 1985. Interest rate and output price uncertainty and industry equilibrium for non-renewable resource extracting firms. *Resources Energy* 10:1–14.